4 STELLAR EVOLUTION

Introduction

Like other animate objects in this universe, a star is born, lives for a certain time and finally dies. **Stellar evolution is the process by which a star undergoes a sequence of radical changes during its life time.** During stellar evolution following changes are expected to follow protostar, premain sequence stage, main sequence stage. During the final stage star may undergo a nova or supernova explosion to become a red giant or supergiant. Depending upon the mass of the star it may end up with white dwarf or neutron star or a blackhole.

Birth of a star

When we look at a clear night sky we can see the gas clusters here and there. It contains mostly hydrogen (about 75%) 24% helium and the remainder such as N_2, O_2, CO_2, etc. called metals. If by accidently some denser part of the gas cluster occurs, then the gas particles, surrounding it are being attracted towards the denser part due to gravitational force. Through millions of years millions and millions of hydrogen atoms accumulate over a region. Hence forms a sphere of gas. This tight cluster of atoms formed by accident and held in grip of its own gravity called a protostar.

As the proto star consists of millions of hydrogen atoms it experiences a strong gravitational force. Because of this gravitational force protostar begins to contract. **It is called embryo star.** This contraction will go on till it becomes luminous. As the embryo star contracts, atoms of the gas collide with one another frequently with greater and greater speeds. The gas heats up. Eventually the gas will be so hot that when the hydrogen atoms collide they no longer bounce of each other but coalesce to form helium or we can say that hydrogen atoms undergo atomic reactions. In other words, a protostar stops collapsing when the core temperature becomes high enough to trigger hydrogen fusion. As the material pull it together into a ball, the pressure of the gas increases. The gas at the centre of the ball becomes extremely hot when the temperature at the centre reaches about 10 million kelvin. At this temperature hydrogen fusion can occur efficiently by the proton-proton chain reaction. The moment the ignition fusion process occurs will halt any further gravitational collapse of the protostar. **The star's interior structure stabilizes with the thermal**

energy created by nuclear fusion maintaining a balance between gravity and radiation pressure. This important act of balancing is called gravitational equilibrium. It is also sometimes referred to as hydrostatic equilibrium. The star is now a hydrogen burning main sequence star.

The time taken for the formation of a protostar to the birth of a main sequence star depends on the mass of the star. When the mass of the star increases its life time decreases. For example a high mass protostar may collapse in million years or less while a star with $1M_\odot$ life for 50 million years. This is because $L \propto M^{3.5}$.

The changes that occur to a protostar's luminosity and surface temperature can be shown on a special H-R diagram. This is known as an evolutionary track or a life track of a star. Each point along the stars track (see figure below) represents its luminosity and temperature at some point during its life and so it shows how the protostars appearance changes due to changes in its interior. In figure 4.1 evolutionary tracks for seven protostars of different masses from $0.5M_\odot$ to $15M_\odot$ are shown.

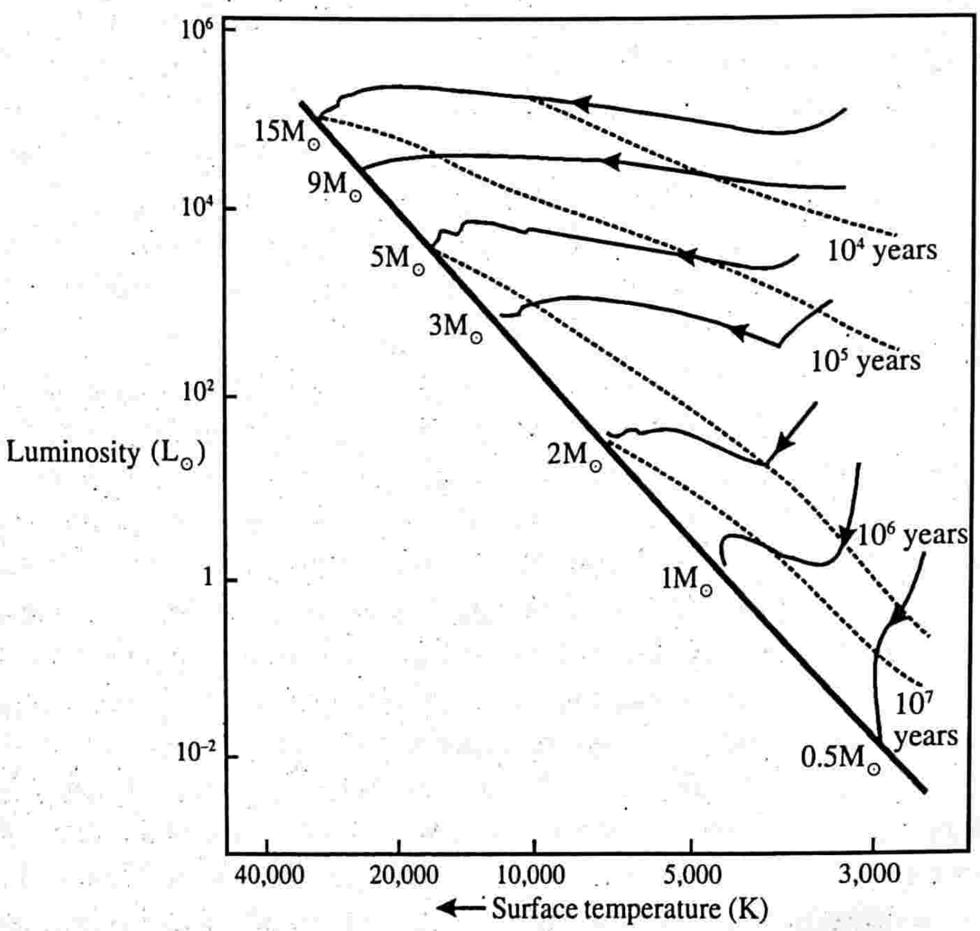


Figure 4.1: Premain-sequence evolutionary tracks (Solid line with arrow mark are evolutionary tracks)

These evolutionary tracks are theoretical models developed by the Japanese astrophysicist C. Hayashi and the phase of a protostar under goes before it reaches the main sequence is called Hayashi phase. Since protostars are relatively cool so the tracks begin at the right side of the H-R diagram. However, the subsequent evolution is very different for stars of differing mass. The masses shown in the H-R diagram is the final mass when it becomes a main sequence star. Also note that the greater the mass, the higher the temperature and luminosity.

A protostar undergoes 4 distinct phase changes before it reaches the main sequence.

Different phases of a star in their life track

Phase 1

The protostar forms from a cloud of cold gas, thus the evolutionary track starts from on right most side of the H-R diagram. However, its surface area is enormous so its luminosity can be very large ($L \propto 4\pi R^2$). This luminosity may be 100 times more than luminous when it becomes a star.

Phase 2

It is due to its large luminosity, the young protostar rapidly loses it energy generated via gravitational collapse. So further collapse proceeds at a relatively rapid rate. Its surface temperature increases slightly during the next million years, but its diminishing size reduces the luminosity. The evolutionary track now progresses almost vertically downward on the H-R diagram.

Phase 3

Now the core temperature has reached 10 million kelvin, hydrogen nuclei fuse into helium. However the rate of nuclear fusion is not sufficient to stop the gravitational collapse of the star. As a result star shrinks and its surface temperature increases. The process of shrinking and heating will result in a small increase in luminosity over the next 10 million years. The evolutionary track now progresses leftward and slight upward on the H-R diagram.

Phase 4

Both the rate of nuclear fusion and the core temperature increase over the next tens of millions of years. Once the rate of fusion is high enough to balance the gravitational collapse, gravitational equilibrium is achieved. The result is that the star settles onto the hydrogen burning main sequence star - a youngster star. (See figure 4.2)

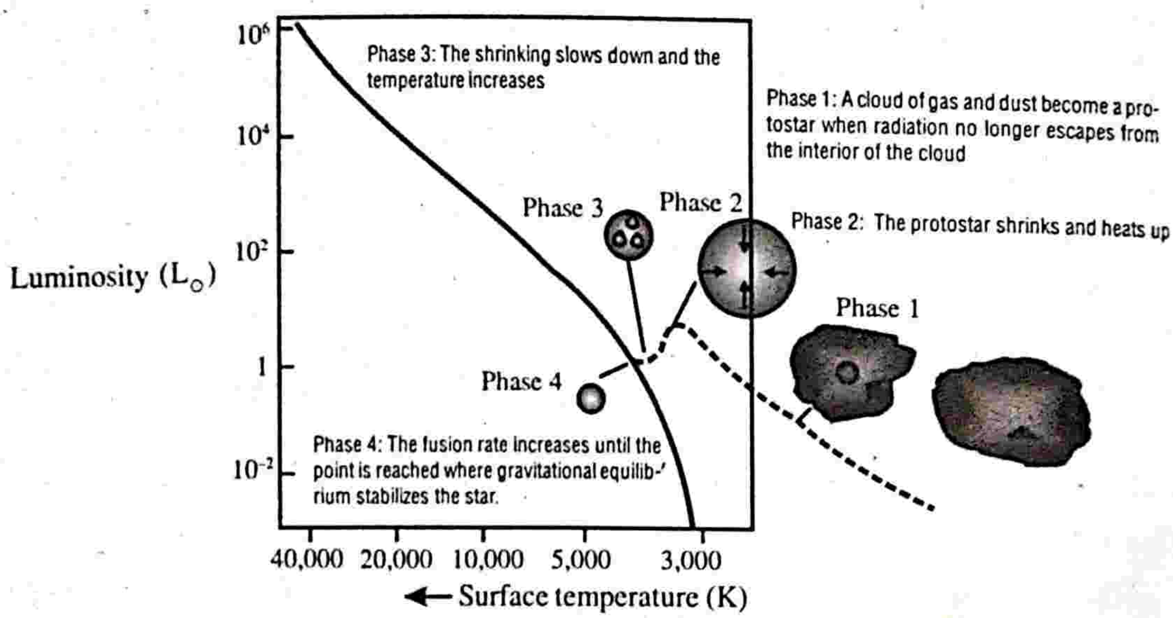


Figure 4.2: The evolutionary track of a protostar with four phases

Note: Four phases of the evolutionary track is discussed by taking $1M_\odot$.

Premain-sequence evolution and the effect of mass

In the last section we found that how a cloud can contract and become a protostar. Protostars have different masses. Here we discuss how masses affect the evolution of protostar before reaching the main sequence.

We begin with a protostar leads to a mass $1M_\odot$ (a star just like Sun). The outer layers of such a protostar are cool and opaque. Since it is opaque the energy released as radiation due to the shrinkage of the inner layers cannot reach the surface. Thus energy moves to the outer layer by convection process. This process is less efficient and slower. As a result of this the temperature remains more or less constant but luminosity decreases as radius decreases due to shrinkage. Thus the evolutionary track moves downward on the H-R diagram. See evolutionary track corresponding to $1M_\odot$ in figure 4.2.

The surface temperature is more or less constant but the conditions inside is changing. The internal temperature increase which reduces the opacity within the protostar and allows the transfer of energy by radiation in the interior regions and by convection in the outer layers. This process is ongoing within the sun now. The net result is that the energy can escape much more easily from the protostar and the luminosity increases. Thus the evolutionary track bending upward and moves left. After an interval of a few million years the temperature within the protostar is high enough - 10 million kelvin - for nuclear reaction to begin. Eventually heat and associated internal pressure increases. This radiation pressure acting outward can balance the gravitational contraction of the star, there by star reaching hydrostatic equilibrium. Now the protostar has reached the main sequence - It is now a main sequence star.

A protostar with a mass of about or greater than $4M_\odot$ contract and heat up at a more rapid rate and so the hydrogen burning phase begins earlier. The net result is that the luminosity stabilizes at approximately its final value, but the surface temperature continues to increase as the protostar continues to shrink. In the H-R you can see nearly constant luminosity (almost a straight line). This is also true for $9M_\odot$ and $15M_\odot$.

An increase in mass will result in a corresponding increase in pressure and temperature in the interior of a star. In very massive stars there is a much greater temperature difference between the core and the outer layers. This allows convection to occur much deeper into the stars interior regions. In contrast, the massive star will have very low density out layers, so energy flow in these regions are easily performed by radiative process.

The main difference between stars of mass greater than $4M_\odot$ and less than $4M_\odot$ is that a star with a mass greater than $4M_\odot$ will have convective outer layers.

Stars with mass less than $1M_\odot$ have a very different internal structure. In these protostars, the interior temperature of the protostar is insufficient to ionise the inner region which is thus too opaque to allow energy flow by radiation. The only way to transport energy is the convection process. The radiative, convective and mass dependence are shown in figure 4.3.

If may be noted that all the evolutionary tracks end at the main sequence where nuclear reactions produce energy by converting hydrogen into he-

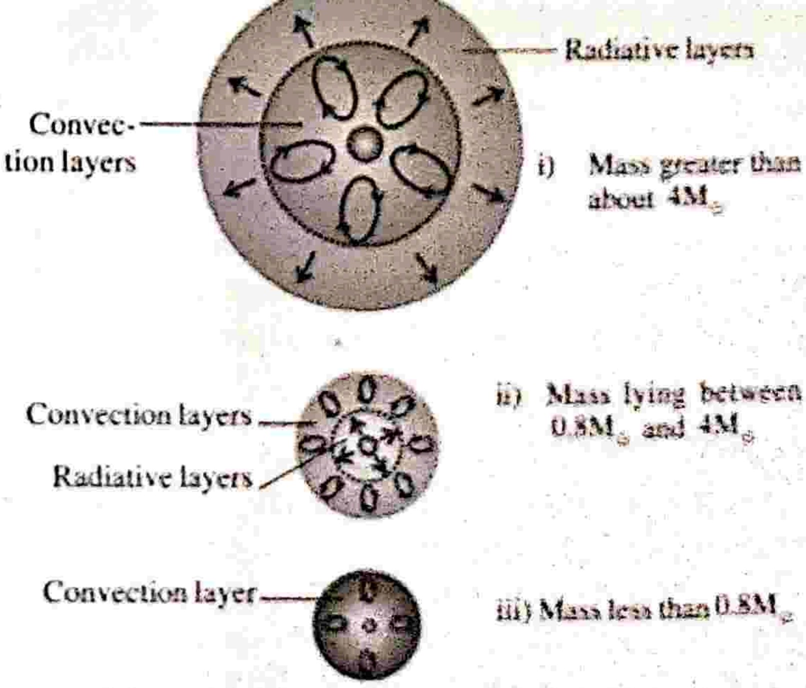


Figure 4.3: Mass and energy flow dependence

lium. Moreover almost all stars in the main sequence are in hydrostatic equilibrium. Thus main sequence is represented by mass-luminosity relationship. The greater the mass the greater the luminosity. The luminosity versus mass is plotted in figure 4.4. A star of mass $10M_{\odot}$ has about $300L_{\odot}$.

For the stars on the main sequence, there is a ratio between the mass and the luminosity. This ratio gives us the life time of the star in the main sequence.

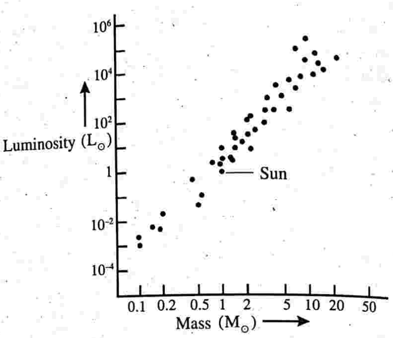


Figure 4.4: Mass-luminosity graph

One important point to be noted is that when a star reaches on the main sequence almost all stars spend most of lives on the main sequence. That is stars live 90% of their lifetimes as a younger star. The remaining 10% time is spent in the aged stage such as giant, supergiant white dwarf, neutron stars and blackholes

Finally we say that masses of stars have limits. It has been theoretically deduced that stars above 150-200$M_{\odot}$ cannot form. If a star of mass above $150M_{\odot}$ is formed it generates so much gravitational energy which cannot be balanced by the radiation pressure. Such stars undergo implosion and tear themselves apart. There is also a lower limit for the formation of stars. It is less than $0.08M_{\odot}$. The stars with a mass less than $0.08M_{\odot}$ can never achieve the 10 million kelvin core temperature necessary to initiate nuclear fusion. Such stars are called failed stars. They slowly radiate their energy till it becomes cool. These objects are called brown dwarfs and seem to occupy between planet and stars. Brown dwarfs radiate energy in the infrared region, so it is very difficult to detect them. A brown dwarf of mass $0.05M_{\odot}$ was detected in the year 1995 and named as Gliese 229 B.

Galactic clusters

Usually stars do not form in isolation. There is an exemption forth this, in 2006 it has been concluded that stars can also form in isolation. Here we discuss about star clusters. We found that stars are formed from nebulae which is a sphere of gas containing hydrogen, nitrogen, metals, dust particles etc. A nebulae can contain materials that could form hundreds of stars. So stars tend to form in groups or clusters. The stars form out of the same nebulae need not have the same mass. That is stars may have different masses. It is due to the difference in mass they reach the main sequence at different times. This is because high mass stars evolve faster than low mass stars. For example, a $1M_{\odot}$ protostar takes about 20 million years to become a main sequence star while $12M_{\odot}$ star may take only 20,000 years when high mass stars are shining brightly as stars, the low mass stars may not have begun shining. In this situation the intense radiation emitted by bright stars may disturb the normal evolution of the lower mass stars and so reduce their final mass.

When time passes the group of stars gradually get dispersed. Since the massive stars have much shorter life times they may not be able to escape from their birth place, where as smaller stars which have long life time may escape from their birth place.

If a cluster containing several thousand stars, their combined gravitational pull towards the centre will slow down the dispersion of the group. Thus clusters can be divided into two, globular clusters and open clusters. Open clusters are called galactic cluster. The closed clusters contain the oldest population of stars where as galactic clusters contain youngest star population.

A small collection of gravitationally bound younger stars containing 10 to 100 stars without having particular shape is called a galactic cluster. Stars in the galactic clusters can be distinguished. Pleiads (Karthika) and Hyades (Rohini) are examples of galactic clusters. The members of galactic cluster need not have the same brightness. Some are bright and some are faint stars. **The stars that makeup a galactic cluster are called population I stars,** which are metal rich and usually found in or near the spiral arms of the galaxy. The size of galactic cluster can from a few dozen *ly* to about 70 *ly*.

Galactic clusters are dissimilar in appearance and vary in character. This is due to their circumstances of birth. It is the interstellar cloud that determines both the number and types of stars that are born. Factors such as size, density, turbulence, temperature and magnetic field all play a role as the deciding parameters in star birth. In the case of giant molecular clouds (GMC) the conditions can give rise to both O and B type stars along with solar type dwarf stars, where as in small molecular clouds (SMC) only solar type stars will be formed. An example of SMC is the taurus dark cloud which lies beyond the pleiads star cluster.

By observing a star cluster we can study the process of star formation and the interaction between low and high mass stars. For example see H-R diagram for NGC 2264 cluster located in monoceros (unicorn) constellation. From the diagram it can be seen that the hottest star with a temperature of about 20,000 K almost reached main sequence while stars with temperatures about 10000 K and below have not reached main sequence. It is concluded that this cluster is very young only two millions years old and it is at a distance of 800 pc from earth.

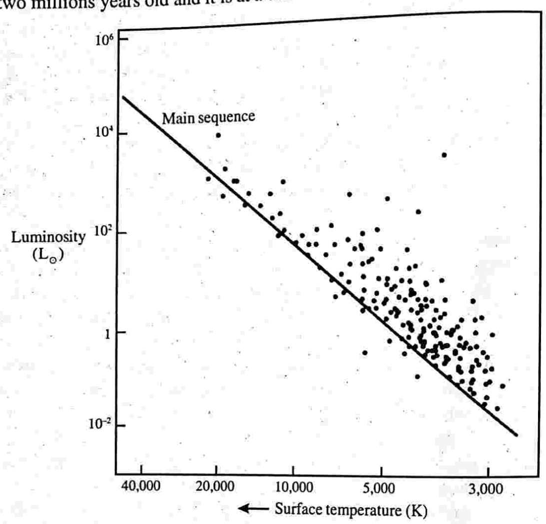


Figure 4.5: H-R diagram of a cluster NGC 2264

So far thousands of galactic clusters have been discovered, only a few are observed to be at distances greater than 25° above or below the galactic equator. Some parts of the sky are very rich in clusters. The constellations cassiopea and puppis (Amaram) contain large number of clusters.

Star formation triggers

Here we discuss about what are the causes of protostar formation. There are three mechanisms by which star formation triggers. They have dissimilar origins.

They are

(i) The spiral arms of a galaxy

(ii) Expanding H II regions

(iii) Supernovae

The spiral arms of a galaxy

We found that spiral arms of galaxies are a prime location for star formation. This is because the gas and dust clouds temporarily pile up as spiral arms orbit around the centre of galaxy. In such a spiral arm the molecular clouds are compressed as it passes through the region. In the molecular cloud's densest regions vigorous star formation occurs.

Expanding H II regions

Massive stars (O type and B type) emit immense amount of ultraviolet radiation. This causes the surrounding gas to ionise and an H II region is formed within the molecular cloud. The strong stellar wind and ultraviolet radiation curve out a cavity within the molecular cloud into which the H II region expands. The stellar wind is moving at supersonic speed as a result a shock wave associated with this supersonically expanding H II region then collides with the nest of the molecular cloud. This process compresses the cloud there by star formation begins to occur. This mechanism is occurring in orion nebula. The four stars of the trapezium are ionising the surrounding material. The nebula is located at the edge of a giant molecular cloud of mass 5,00,000 $M_{\odot}$.

Supernova

Supernova is a catastrophic explosion of a star in its old age. In this explosion the out layers of the star are tear into pieces and thrown away. The ejected outer layers move in space with an incredible speed, may be several thousand kilometres per second results in shock waves. This shock waves impact the material in the interstellar medium triggering further star formation.

The Sun

The Sun is the nearest star to us which lies on the main sequence. The Sun has been in the main sequence for the last 50 million years and it will remain there for another 50 million years. Here we discuss on the internal structure, the means of energy production and the manner in which energy transported from its source to us on earth.

The internal structure of the Sun

The internal structure of the sun mainly comprises 5 parts. They are (i) photosphere (ii) convection zone (iii) plasma zone (iv) radiation zone and (v) core

(i) Photosphere

It is the visible surface of the sun which has a temperature of 5000 K. Though it looks like a well defined surface from the earth, it is a gas less dense than the earth's atmosphere. Both the density and temperature steadily increase as we go towards the core of the Sun.

(ii) Convection zone

Convection zone is the very turbulent area beneath the photo sphere. In this area energy generated in the core of the Sun travel upward, transported by rising the columns of hot gas and the falling of cool gas taking place. This process is called convection, hence the name convection zone.

(iii) Plasma zone

Descending deeper through the convection zone the pressure and density increase quite substantially along with temperature. When we reach at a stage where the gas is under extreme conditions of pressure and temperature becomes ionised. This region is called plasma region. Plasma is a collection of positively charged ions and free electrons. The temperature of this region is about 2 million kelvin. This region absorbs photons. The density of this region is far greater than that of water.

(iv) Radiation zone

This region is in the more stable plasma state and one third of the way down to the centre. The temperature of this region is about 10 million kelvin. Here the energy is transported outward primarily by photons of X-ray radiation.

(v) Core

The central region of the Sun is called the core of the Sun. The temperature is about 15 million kelvin. This is the region where nuclear process takes place. Hence it is also called as nuclear burning zone. Here hydrogen is being converted into helium. The density of this region is about 150×10^3 kg m^{-3}. This means that the density is about 150 times that of water. The radius of the inner core is about 25% of the total radius of the sun. Beyond this radius (upward) practically no nuclear reaction takes place.

See also the figure given below.

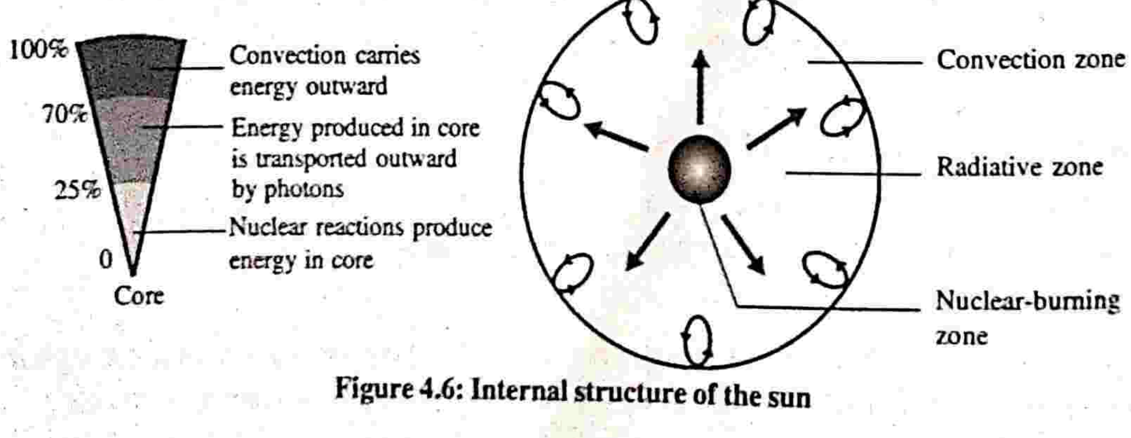


Figure 4.6: Internal structure of the sun

The inner core of the sun contains only about 34% hydrogen whereas the outer core contains 71% hydrogen. The reason is that for the last 4.6 billion years hydrogen has been converting into helium. The luminosity of the Sun is 3.8×10^{26} joules per second. If we could somehow capture all of the energy for one second, it would be sufficient to meet all current energy demands for the human community for the next 50,000 years. But remember that only a tiny fraction of this reaches the earth.

According to the current model of energy production in the Sun, nuclear fusion is the source. With this energy the Sun will shine for 10 billion years. Among this 4.6 million years elapsed and the remaining 5.4 million years further to go by the Sun. According to this model the size of the Sun is stable. This stability is maintained by balancing the gravity pull acting inward and radiation pressure acting outward.

The proton-proton chain reaction

The main source of the energy of the sun is through the process of nuclear reaction. Sun contains immense amount of the hydrogen. The fusion of hydrogen into helium releasing energy was first proposed by the British astronomer Arthur Eddington in 1920 but the details of the reaction were came out only after 1940.

Hydrogen nucleus contains only one proton whereas helium nucleus contains two protons and two neutrons. So four protons are required to produce a helium nucleus. Collisions of four protons never make a helium nucleus, because no such reaction is found to occur in laboratories. The actual reason is that when protons collide it is due to mutual repulsion they move apart and cannot involve in reaction. For any reaction to occur there are some conditions required. One is that protons have to move with very high velocity. This condition exists in the centre of the Sun. At the core of the Sun, the temperature is about 15 million kelvin and the proton will be travelling at about 1 million kilometers per hour. Even at this fantastic speed the probability of occurring reaction is very small. A single proton would take nearly about 5 billion years to get reacted with another photon. However, as there are so many protons in the Sun's core, every second 10^{34} of them can undergo a reaction.

Now we believe that proton and proton undergo reaction in a series of manner involving two reactions at a time. This is called proton-proton chain reaction. This reaction involves three steps.

Step 1

Two protons fuse to form a deutirium nucleus, a positron and a neutrino.

i.e. $$^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \upsilon$$

The positron β^{+} (a positively charged electron) does not last long, it will soon meet up an electron producing two gamma rays that are absorbed by the surrounding gas. Neutrino rarely interacts with matter and so pass straight out into space.

Step 2

The deuterium now fuses with a proton producing a helium nucleus (^3He) and gamma rays. The ^3He nucleus consists of consists of two protons and one neutron.

i.e. $$^2H + {}^1H \rightarrow {}^3He + \gamma$$

Step 3

Finally two ^3He nuclei combine to form ^4He nucleus and give back two protons.

i.e. $$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$$

So the net result of reaction is

$$6\,{}^1H \rightarrow {}^4He + 2\,{}^1H$$

The total energy released in this process worked out is 26.72 MeV. So the complete reaction can be written as

$$6\,{}^1H \rightarrow {}^4He + 2\,{}^1H + 24.72 \text{ MeV}.$$

Calculation of energy released

In proton-proton chain reaction though 6 protons take part, it gives two proton, only 4 protons converted into ^4He nucleus.

Mass of one proton, $m_p = 1.6726 \times 10^{-27}$ kg

Mass of four protons $= 4 \times 1.6726 \times 10^{-27}$ kg

$= 6.6904 \times 10^{-27}$ kg

Mass of helium nucleus $= 6.645 \times 10^{-27}$ kg

$\therefore$ The difference in mass $= 6.6904 \times 10^{-27} - 6.645 \times 10^{-27}$

$$\Delta m = 0.0454 \times 10^{-27} \text{ kg}.$$

This difference in mass is converted into energy according to Einstein's mass-energy relation $E = mc^2$.

$\therefore$ The energy released, $\Delta E = \Delta mc^2 = 0.0454 \times 10^{-27} \times (3 \times 10^8)^2$

$$\Delta E = 0.4086 \times 10^{-11} \text{ J}$$

Converting this into MeV, we get

$$\Delta E = \frac{0.4086 \times 10^{-11}}{1.6 \times 10^{-13}} \text{MeV}$$

$$\Delta E = 25.54 \text{ MeV}.$$

It may be noted that the Sun converts about $600 \times 10^9 \text{kg}$ of matter into $596 \times 10^9 \text{kg}$ of helium in every second. The missing $4 \times 10^9 \text{kg}$ of matter are converted into energy. A rough calculation shows this figures.

We found that 4 protons having mass $6.6904 \times 10^{-27} \text{kg}$ is converted into helium of mass $6.645 \times 10^{-27} \text{kg}$.

$$\therefore \qquad \frac{\Delta m}{m} = \frac{0.0454 \times 10^{-26}}{6.6904 \times 10^{-27}} \simeq 0.7\%.$$

Let M be amount of hydrogen converted into helium in every second. Out of which only 0.7% is converted into energy. i.e. $M \times \frac{0.7}{100} c^2$ energy is released. But the energy released by the Sun in one second is $3.8 \times 10^{26} \text{J s}^{-1}$ (Luminosity of Sun)

$$\therefore \qquad M \times \frac{0.7}{100} \times (3 \times 10^8)^2 = 3.8 \times 10^{26}$$

or

$$M = \frac{3.8 \times 10^{26} \times 100}{0.7 \times (3 \times 10^8)^2} \simeq 600 \times 10^9 \text{kg}.$$

0.7% of this is $600 \times 10^9 \times \frac{0.7}{100} \simeq 4 \times 10^9 \text{kg}$ is converted into energy.

$\therefore$ Mass converted into helium is $600 \times 10^9 - 4 \times 10^9 = 596 \times 10^9 \text{kg}$

Energy transport from the core to the surface

Energy produced in the central region of the Sun in the form of X-ray photons flows outward towards the surface. If the Sun were transparent these photons reach the surface after 2 seconds. The Sun is transparent means there are no interactions between photons and electrons. If there were no interactions between photons and electrons, time taken by the photon

$$t = \frac{x}{v} = \frac{\text{radius of the sun}}{\text{speed of light}}$$

$$t = \frac{6.9 \times 10^8}{3 \times 10^8} = 2.3 \text{ s.}$$

i.e. light takes only 2.3 seconds to exit the Sun if there were no interactions.

But the Sun's gases are not transparent. So during the passage of photons, every now and then they collide with nearby electrons. The electron can actually absorb the photon and takes its energy. This causes the electron to jump out of its orbit to new higher orbit. Since the electron can only exist at specific energy levels, this usually results in the electron giving off a photon and goes back to its stable orbit. So technically a photon born in the middle of the Sun never makes it to the surface. It is always absorbed and re-emitted as another photon. Photons are continuously absorbed and re-emitted throughout the interior of the Sun. The emitted photon will not necessarily emitted in an outward direction but rather a totally random direction. This results in an apparent dance like motion of the photons inside the star. This slow dance like motion of photons is called random walk. By such a random walk photon travels along a zig-zag path from the centre of the Sun to its outer surface. Finally, the photon escapes from the Sun's surface. During their random walk, the photons which are X-ray photons at the core become optical photons by the time they reach the surface.

The above discussion shows that there is a considerable time delay before energy produced at the core reaches the surface. On an average photon takes about 1.7×10^5 years to reach the surface. **This time taken by a photon to leave out of the Sun is called photon diffusion time.**

A simple calculation confirms this long delay in time.

Photon diffusion time $\tau = \dfrac{\text{Total photon energy}}{\text{Luminosity}}$

$$\tau = \frac{1.4 \times 10^{39}}{3.8 \times 10^{26}} = 3.68 \times 10^{12} \text{ s}$$

$$\tau = \frac{3.68 \times 10^{12}}{3.15 \times 10^{7}} \text{ years}$$

or $\tau = 1.17 \times 10^5$ years.

The above discussion brings us two important informations. Firstly, when we observe sunlight, we know nothing about what is going on at the core at the moment of observation. This is because the light we see now created in the core some thousands of years ago. Secondly suppose Sun ceases to produce energy, we can notice this only after thousands of years. This implies that the brightness of Sun is very in sensitive to changes in the energy production.

Binary stars

The stars that may appear to the naked eye to be just one star, but on observation with either binoculars or telescopes resolves themselves into two stars are called binary stars or double stars. Many stars appear as double stars due to their position in the same line of sight as seen from the earth. These are called optical doubles.

Binary stars are actually pairs of stars gravitationally bound and revolve about a common centre of mass with a common period.

Classification of binary stars

Binary stars are classified into four. They are (i) spectroscopic binaries (ii) eclipsing binaries (iii) astrometric binaries and (iv) visual binaries.

(i) Spectroscopic binaries are binaries which cannot be resolved even by largest telescopes. These binaries can be distinguished by analysing their spectra.

(ii) Eclipsing binaries are binaries in which one of the stars moves during its orbit in front of its companion. The binary star Algol belongs to Perseus constellation is an example for eclipsing binary.

(iii) In astrometric binaries one star is too faint to be seen and its presence is inferred from the perturbations in the motion of the other star. The binary star Sirius belongs to α Canis major (big dog) constellation is an example for this.

(iv) Visual binaries are binary stars in which two are far enough apart to be seen separately by an optical telescope. In this one of them is bright and the other is faint. The brighter star is called primary star and the faint one is called secondary or companion star. The two stars in this binary can be observed visually hence the name.

The study of binary stars are very important. This is because by observing the period of motion of binary we can determine their mass, which will help us to determine the evolutionary processes of stars.

Here we discuss only about visual binaries. To locate visual binaries two important terms are to be studied. They are separation and position angle (PA).

Separation

Separation is the angular distance between the two stars measured in seconds of arc. This angle is measured from the brighter star to the fainter.

Position angle

Position angle is the relative position of the secondary star with respect to the primary star. It is measured in degrees. Now our aim is to depict separation and position angle of a binary in a graph. For this imagine a coordinate system whose origin is the primary star. The north direction is assigned as 0°, due east 90°, due south 180°, due west 270° and back to 0° as shown in figure.

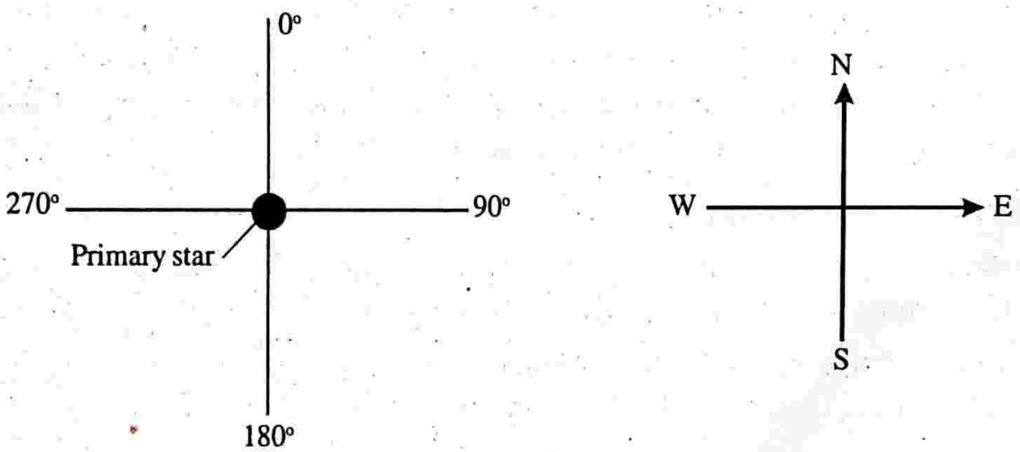


Figure 4.7

In each year calculate the separation and position angle and mark it on the graph. For example the separation and position angle of the star γ Virginis (a visual binary) is plotted below.

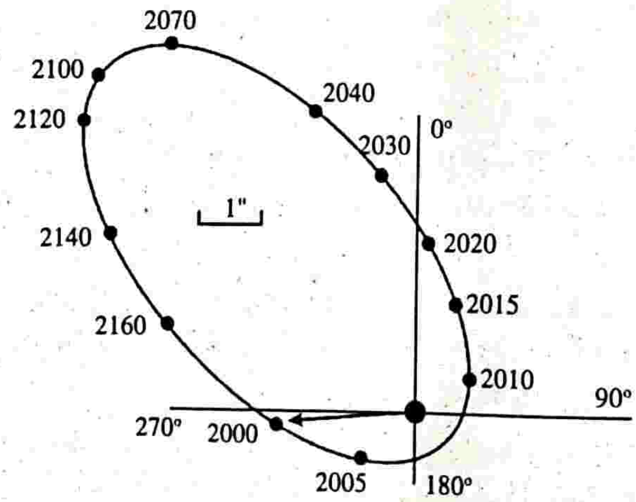


Figure 4.8: Separation and position angle of γ Virginis

From the graph it can be readily seen that in the year 2000 the separation between the two stars is $1.8''$ at PA of 267°. It may also be noted that the separation and PA are constantly changing. Stars with long period of time will have no appreciable change in PA for several years.

Masses of orbiting stars

The masses of visual binary can determined by using Kepler's third law ($T^2 \propto a^3$) and Newton's law of gravitation. The first experimental evidence of Newton's law of gravitation $F = \frac{Gm_1m_2}{r^2}$ came from the observation of time period of binary stars.

Consider a binary system of two stars A and B of masses m_A and m_B (where $m_A > m_B$) forming a pair and bound by their mutual gravitational attraction. These stars are revolving around their common centre of mass (CM) of the system in their elliptical orbits such that CM remains constant. See figure below.

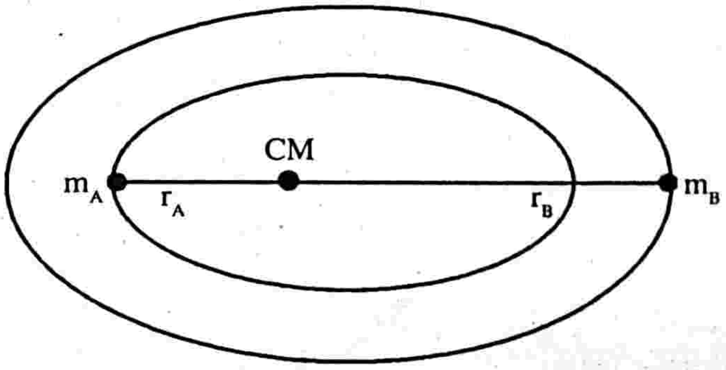


Figure 4.9

Let r_A be the distance of star A from the CM and r_B be the distance of star B from the CM. Then

$$r_A + r_B = r \qquad \text{..... (1)}$$

the separation between the two stars.

From the definition of centre of mass we have

$$m_A r_A = m_B r_B \qquad \text{..... (2)}$$

From eq (1), $\quad r_B = r - r_A$

Put this in equation (2), we get

$$m_A r_A = m_B (r - r_A)$$

or $$r_A = \frac{m_B r}{m_A + m_B} \qquad \text{..... 4(a)}$$

$$r = \frac{(m_A + m_B)}{m_B} r_A \qquad \text{..... 4(b)}$$

The gravitational force exerted on the star of mass m_A by the star of mass m_B is

$$F = \frac{Gm_A m_B}{r^2}$$

If the path of the orbit is circular, the centripetal force required $(m_A r_A \omega^2)$ is supplied by the gravitational force $\left(F = \frac{Gm_A m_B}{r^2}\right)$.

i.e. $$\frac{Gm_A m_B}{r^2} = m_A r_A \omega^2 \qquad \text{..... (5)}$$

Substituting for r from eqn 2, we get

$$\frac{Gm_A m_B}{\left(\frac{m_A + m_B}{m_B}\right)^2 r_A^2} = m_A r_A \omega^2$$

or $$\frac{m_B^3}{(m_A + m_B)^2} = \frac{r_A^3 \omega^2}{G}$$

Using $\omega = \frac{2\pi}{T}$ where T is the time period of the binary star.

$$\frac{m_B^3}{(m_A + m_B)^2} = \frac{r_A^3 4\pi^2}{T^2 G}$$

Substituting for r_A from eq 4(a), we get

$$\frac{m_B^3}{(m_A + m_B)^2} = \frac{m_B^3 r^3}{(m_A + m_B)^2} \frac{4\pi^2}{T^2 G}$$

or $$T^2 = \frac{4\pi^2}{G(m_A + m_B)^2} r^3 \qquad \text{..... (6)}$$

This is the Kepler's third law $T^2 \propto r^3$.

or $$m_A + m_B = \frac{4\pi^2}{GT^2} r^3 \qquad \text{..... (7)}$$

Knowing the time period (T) of the binary star and the separation between the two stars (r). The total mass of binary star can be determined. Determining one of the masses of binary, the other can be determined.

With much more rigorous calculation (see example 2), considering elliptical orbits, we get

$$m_A + m_B = \frac{4\pi^2}{GT^2} a^3 \qquad \text{..... (8)}$$

Where a is the semi major axis of the elliptical orbit of one star and T is the time period of one star to complete one rotation around the other.

If we express masses m_A and m_B in terms of solar mass $m_\odot$, a in astronomical unit and T in years, the value of $\frac{4\pi^2}{G}$ turns out to be 1. Thus we have

$$m_A + m_B = \frac{a^3}{T^2} \qquad \text{.....(9)}$$

Determination of T and a

To determine the total mass of the binary, we have to determine the time period of the one star with respect to the other and the semi major axis of the orbit. For this we determine the stars orbits by observing one star for several years. This may take a few years or tens of years, but we can eventually determine the time needed (T) for one star to completely orbit the other. Knowing the orbit of one star with respect to the other we can calculate the semi major axis.

Example 1

Consider the double star system Sirius A and Sirius B. The orbital period of the binary is 50 years and the semimajor axis is 19.8 AU. Determine their combined mass.

Solution

We have $$m_A + m_B = \frac{a^3}{T^2}$$

$$m_A + m_B = \frac{19.8^3}{(50.1)^2} = \frac{7762.4}{2510}$$

$\therefore$ $$m_A + m_B = 3.09\ m_\odot$$

Example 2

A binary star system consists of two stars s_1 and s_2 with masses m and 2m respectively separated by a distance r. If both s_1 and s_2 individually follow circular orbits around the centre of mass with speeds v_1 and v_2. Calculate $\frac{v_1}{v_2}$.

Solution

From the figure we have

$$mr_1 = 2mr_2$$

$$r_1 = 2r_2$$

but $$r_1 + r_2 = r$$

$$r_1 + \frac{r_1}{2} = r$$

$$r_1 = \frac{2}{3}r \quad \text{and} \quad r_2 = \frac{1}{3}r$$

For the star s_1

$$\frac{Gm2m}{r^2} = \frac{mv_1^2}{r_1}$$

$\therefore$ $$v_1^2 = \frac{2Gm}{r^2}r_1 \qquad \text{..... (1)}$$

For the star s_2

$$\frac{Gm2m}{r^2} = \frac{2mv_2^2}{r_2}$$

$$\therefore \qquad v_2^2 = \frac{Gm}{r^2} r_2 \qquad ..... (2)$$

$\frac{eq\ (1)}{eq\ (2)}$ gives
$$\frac{v_1^2}{v_2^2} = 2\frac{r_1}{r_2}$$

$$\frac{v_1}{v_2} = \sqrt{2\frac{r_1}{r_2}} = \sqrt{\frac{2 \cdot \frac{2}{3}r}{\frac{r}{3}}} = 2$$

Lifetimes of main sequence stars

So far we have been discussing how a star is formed, how, the mass of stars can be determined and how long does it take to become a star etc. Now we shall discuss how long a star will remain on the main sequence and what are the changes in the internal structure of star.

All stars on the main sequence are fundamentally alike in their cores. This is because it is here that stars convert hydrogen into helium. **The process of converting hydrogen into helium is called core hydrogen burning.**

The time that stars spend on the main sequence, the stars with smaller masses live longer.

Main sequence lifetimes for stars of different masses are depicted in the figure given below.

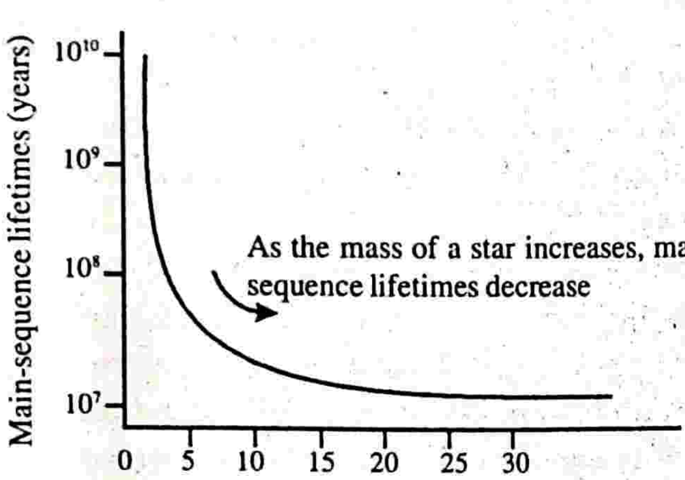


Figure 4.10: Main-sequence lifetimes for stars of different mass

It may also be noted that high mass stars are extremely bright this is because high mass stars use up their fuel hydrogen at a fast rate. This will in turn reduce their lifetime. For example O-type stars are much more massive than M-type stars. Thus O-type stars use their fuel at faster rate than M-type stars. Hence the luminosity of O-types stars higher and lifetimes are shorter compared to M-type stars. O-type stars have luminosity $80,000\,L_\odot$ and lifetime 3×10^6 years whereas M-type stars have luminosity $0.08\,L_\odot$ and lifetime $56,000\times10^6$ years. The mass, luminosity and life time of some stars are given in the table 4.1.

Table 4.1 Mass,, spectral class, and main-sequence lifetimes

Mass, $M_\odot$	Temperature, K	Spectral class	Liminosity, $L_\odot$	Main-sequence lifetime, 10^6 years
25	35,000	O	80,000	3
15	30,000	B	10,000	11
3	11,000	A	60	640
1.5	7000	F	5	3600
1	6000	G	1	10,000
0.75	5000	K	0.5	20,000
0.5	4000	M	0.08	56,000

Red giant stars

When stars are in the main sequence, they use up their hydrogen fuel and converting into helium producing huge amount of energy. This will go on occurring for millions and millions of years. When all the hydrogen has been used up, the energy production ceases. At this time star begins to use up its gravitational energy to supply its energy needs. Thus the core will start to cool down so the pressure decreases with the result that the outer layers of the star will begin to compress the inner core by its weight. The effect is to increase the temperature of the core and heat flows outward from the core. This heat formed is not due to nuclear reactions but due to conversion of gravitational energy into thermal energy.

In a short time the hydrogen layers surrounding the core become too hot to start nuclear reactions. **This conversion of hydrogen into helium taking place only in a thin shell around the core. This process is called shell hydrogen burning.** See figure 4.10. This time core is helium rich and outer layer is hydrogen rich. The shell where energy production occurs is very thin.

Figure 4.10: Star with shell hydrogen-burning

For a star like Sun, the hydrogen consuming shell develops immediately after the core ceases production of energy so that output energy is almost a constant. For massive stars the time interval to change from core nuclear fusion phase to the beginning of the shell hydrogen burning phase is of the order of thousand to million years.

The new supply of energy and thus heat further increase the rate of shell hydrogen burning. The by-product of the hydrogen fusion which is helium falls into the core which is already rich in helium. It heats up the core there by core again contracts and its mass increase. The core compression results in increase of temperature to about 15 million kelvin to 100 million kelvin.

At this temperature stars inner core is invisible to our eyes. Now we have a contracting inner core star with increased flow of heat and a ever expanding shell of hydrogen burning. As a result of this stars luminosity increases quite substantially. The increased temperature inner core increases the pressure, which makes the outer layer of the star to expand many times of their original radius. The tremendous expansion of the outer layer makes it cool. The temperature comes to about 3500 K. Thus the out layer seems to be in red colour. This giant red in colour star is called red giant.

There are so many red giants that are observable in the night sky. Some of them are Capella A, Arcturus, Aldebaren, Pollux, Mirah, etc.

According to the present knowledge most of the stars with a mass greater than or equal to the sun's will eventually become red giants. This means that one day our Sun becomes a red giant and large enough to swallow up mercury and venus.

Helium burning

When a star becomes a red giant the inner core is full of helium nuclei which is the byproduct of hydrogen burning nuclear reaction. Then helium will be next fuel for burning. This is the helium burning phase. As the star becomes a red giant the core temperature is too low to initiate helium burning. At the same time the hydrogen burning shell surrounding adds mass to the core, resulting in further contraction of the core. Owing to this core becomes denser and the temperature increases substantially. As the temperature increases the electrons in the gas become degenerate. This degenerate electrons resist further contraction of the core and the internal temperature can no longer affect the internal pressure.

As the hydrogen shell continues to burn, the degenerate core grows even hotter and the temperature becomes 100 million kelvin core helium burning begins, converting helium into carbon and oxygen releasing energy. During this state of star's life its size is only about 1AU in radius and luminosity is 1000 times brighter than the Sun. Once again, the old star which left the main sequence, obtained nuclear energy.

The helium burning in the core fuses three helium nuclei to form a carbon nuclei. This is called triple alpha process. This occurs in two steps.

Step 1

Two helium nuclei combine to form an isotope of beryllium.

i.e. $$4He + 4He \longrightarrow {}^{8}Be$$

This isotope of beryllium is very unstable and quickly breaks up into two helium nuclei. But in the extreme conditions in the core, a third helium nucleus fuses with beryllium before the break up and a stable isotope of carbon is formed and energy released in the form of γ-ray photon (γ)

i.e. $${}^{8}Be + {}^{4}He \longrightarrow {}^{12}C + \gamma$$

Since helium nucleus is also called as α-particle, the process is called triple alpha process.

Step 2

The carbon nuclei so formed can also combines with another helium nuclei producing stable isotope of oxygen and releases additional energy.

i.e. $${}^{12}C + {}^{4}He \longrightarrow {}^{16}O + \gamma$$

These byproducts (carbon and oxygen) of helium burning is called ash.

The formation of carbon and oxygen not only produces more energy but also re-establishes thermal equilibrium in the core of the star. The prevents the core from further contraction due to gravity. This life time of a red giant in the helium burning stage is only 20% as long as the life time it spend burning hydrogen burning on the main sequence. For example the life time of Sun in the main sequence is 10 billion years but it will spend only two billion years in the helium burning phase.

The helium flash

The mass of a star plays a vital role in deciding how helium burning begins in a red giant. If the mass of star is greater than 2-3$M_{\odot}$, the helium burning begins gradually as the temperature of the star approaches 100 million kelvin. Then the triple α process is initiated, but it occurs before the electrons become degenerated. **However if the mass of the star is less than 2-3$M_{\odot}$, the helium burning stage begins suddenly in a process called helium flash.** This is due to the most unusual conditions prevailing in the core of the star.

The energy that is produced by the triple α process heats up the core and its temperature rises. This increase and subsequent rise in energy production can cause the temperature to reach 300 million kelvin. It is due to the rapid heating of the core, a nearly explosive consumption of helium occurs. This is called helium flash. At the peak of the helium flash, the energy output of the core is about 10^{11} to 10^{14} times greater than the solar luminosity. When the temperature of the core becomes 300 million kelvin electrons become non-degenerate and they behave like ordinary electrons in a gas. The result is that the core expands which ends up in helium flash.

It may also be noted that the helium burning in the core lasts for a relatively short time. For example a star like Sun, the period after helium flash will only last about 100 million years which is about 1% of its main sequence life time.

Star clusters, red giants and the H-R diagram

So far we have been dealing with stellar evolution and its ultimate fate starting from protostar to red giant. During this very long processes, we noticed several changes regarding the temperatures, the life times, the luminosities, the phases etc. Now we are going to indicate all these changes in an H-R diagram, so we get evolution track of stars at one glance. This is depicted in the figure given below. Stars are formed from protostars and are about to join main sequence. That is we begin with a youngster star. The following points may be depicted on the H-R diagram.

1. A youngster star is in the main sequence and hydrogen burning is the process taking place and the star is in hydrostatic equilibrium. These stars are often referred to as zero age main sequence stars (ZAMS). This is represented by the curve I on the H-R diagram. From this curve we can read off the temperature and luminosity corresponding to mass of the star.
2. We know that life time of a star depends on its mass, larger mass stars lives shortly. During this life time hydrogen has been burning and converting into helium and the luminosity increases accompanied by an increase in stars radius. So the stars move away from curve I. Finally the stars reach at curve II. This curve represents the end of the hydrogen burning. That is main sequence star is spread over the space between curve I and II.

   This shows that the main sequence on the H-R diagram is a broad band or ribbon like rather than a single curve.
3. When hydrogen fuel has been exhausted the nuclear reaction ceases and there is a sudden fall in temperature. Thus the stars move from left (high temperature) to right (low temperature) on the H-R diagram. This is represented by evolutionary tracks with arrow marks. It may also be recalled that at this phase luminosity

remains almost constant. The core is contracting and outer layers expanding as energy flows from, the hydrogen turning shell (Red giant).

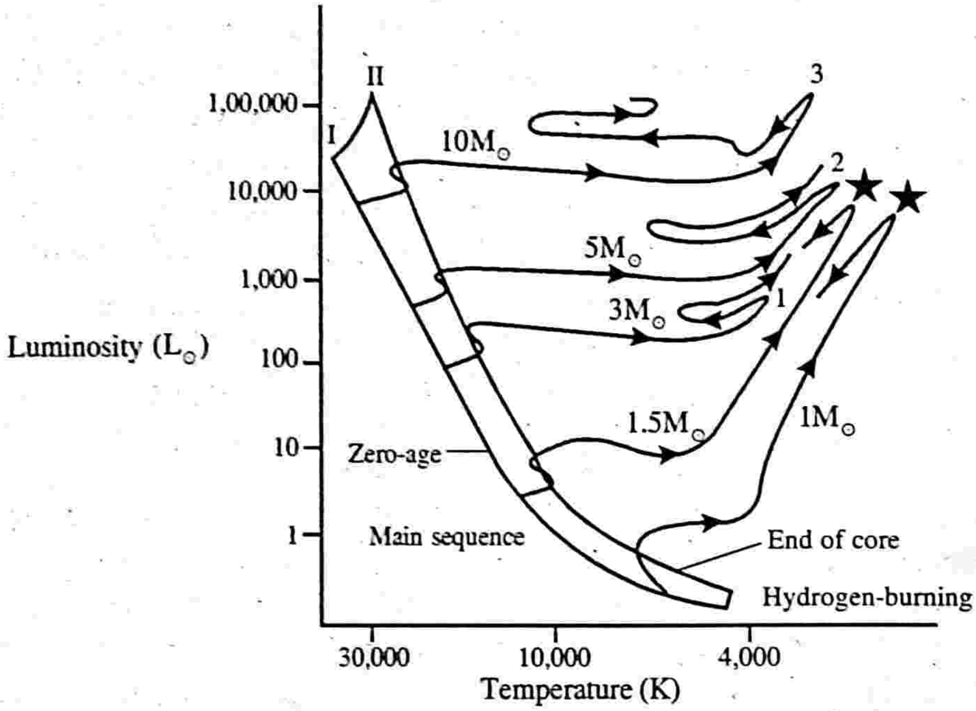


Figure 4.11: Post main sequence evolutionary track for several stars of different masses

4. The cusp of every evolutionary track represents a red giant. When the mass of red giant is small (less than 2-3$M_\odot$) helium flash occurs. This time the star shrinks and becomes less luminous and the temperature rises. So the evolutionary track moves down lower luminosity) and also to left (increase in temperature), on the H-R diagram. This is indicated by two stars symbols on the H-R diagram.

In the case of high mass stars (greater than 2-5$M_\odot$) core helium burning exhibit downward turns on the H-R diagram. See points 1, 2 and 3 marked. The evolutionary track then makes an upward turn to the upper right. This occurs just before the core helium burning begins. After the start of helium-burning, the core expands, the outer layers contract the evolutionary track fall from temporary high luminosities. It may also notice that how the truck moves back and forth on the H-R diagram. This represents the star's adjusting to their new energy supplies.

We can observe the evolution of stars from birth to the helium burning by looking youngster clusters and comparing actual observations with theoretical calculations.

Post main sequence star clusters: The globular clusters

A collection of gravitationally bound stars formed in spherical in shape and found around the galactic centre is called globular cluster.

A cluster contains about 10,000 to one million stars. Since the stars are metal poor they are found to be distributed in spherical shape around the galactic centre with a diameter about 10 *ly* to 300 *ly*. The number of globular clusters is found to increase as we move towards the galactic centre. Towards the galactic bulge there are high concentration of globular clusters. Sagittarius (Dhanu) and Scorpius (Vrichikam) are examples of globular clusters.

The origin and evolution of a globular cluster is very different from that of a galactic cluster. All stars in a globular clusters are very old. Any star massive than G or F-type might have already left the main sequence and moved towards the red giant stage. Thus no formation of new stars within the globular cluster is possible in our galaxy. Thus they are believed to be our galaxies oldest structure. In fact the youngest of globular clusters is still far older than the oldest galactic cluster.

Although the stars within a globular cluster are formed in similar conditions, stars differ in their sizes. However when we look at stars from the earth all seen to be

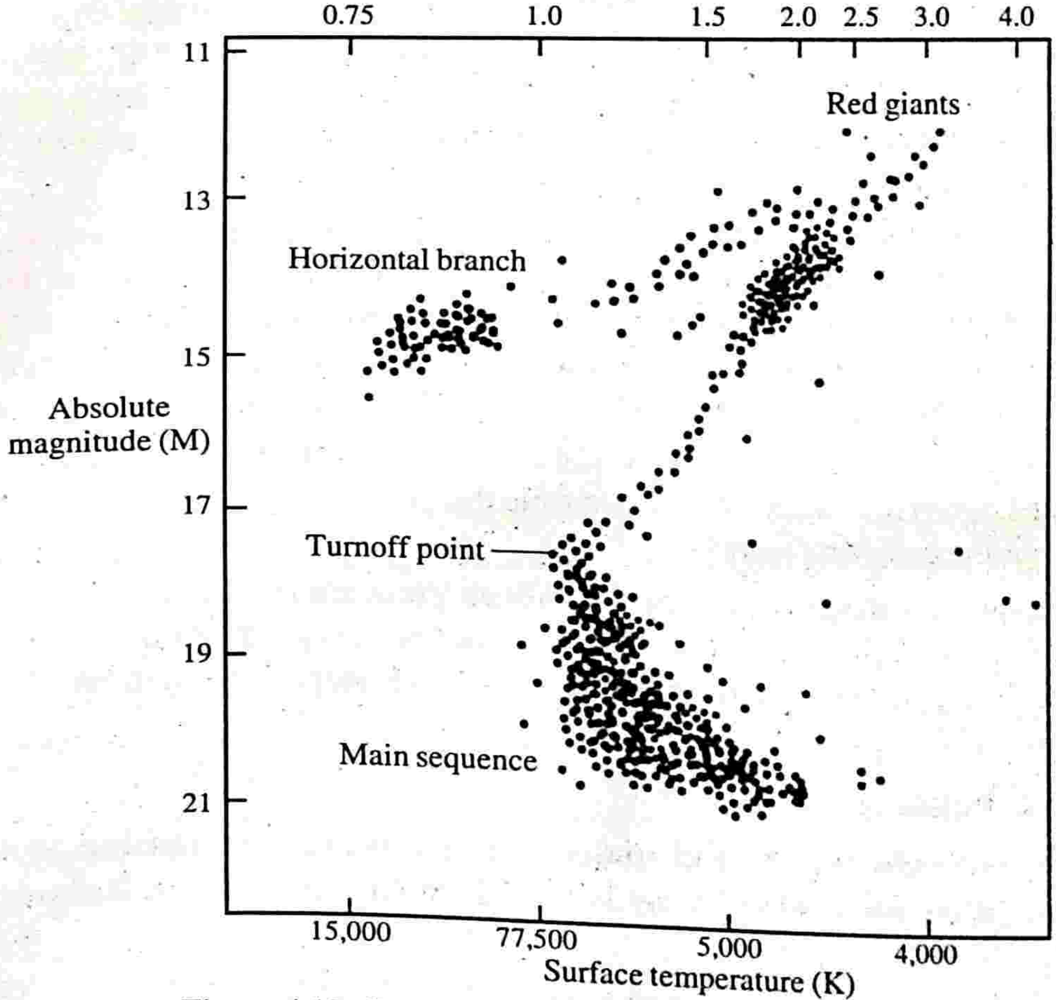


Figure 4.12: Colour-magnitude diagram for the globular cluster M3

about at the same distance. To find out the distance and age of a cluster we draw a special kind of H-R diagram called colour-magnitude diagram. On a colour-magnitude diagram, the apparent brightness is plotted against the colour ratio for many of the stars in a cluster. The colour ratio of a star can tell us the surface temperature of the star, when we compare colour-magnitude H-R diagram with an ordinary H-R diagram we can very well calculate the distance of a cluster. If the stars in a cluster lie at the same distance the apparent brightness (magnitudes) can tell us their relative luminosities. A colour-magnitude diagram for the globular cluster M3 is given figure 4.12.

The following informations are obtained from the colour-magnitude diagram.

1. In the graph we can seen that the upper half of the main sequence has disappeared. This means that all of the high mass stars in a globular cluster have evolved into red giants, a long time ago. The low-mass main sequence stars (lower part of the graph) are very slowly turning into red giants.
2. On the left of the diagram (up) we can see grouping of stars. This is called the horizontal branch. Stars in this horizontal branch are called horizontal branch stars. These stars are low mass, post helium flash stars with luminosity about $50L_\odot$. In these stars there are both core helium burning and shell hydrogen burning. In the future these stars will also move towards the red giant region as the fuel is exhausted.
3. As time passes, the main sequence stars will be smaller and smaller in number. The top of the main sequence, which remains after the specified time can be used to determine the cluster's age and is called the turnoff point. The stars that are at the turnoff points are those that are just exhausting the hydrogen in their cores, so the main sequence lifetime is in fact the age of the star cluster.

Many stars in the globular cluster are visible to optical instruments. Some are even visible to the naked eye. Some stars not visible due to the presence of gases and dust particles near the galactic centre.

The nearest globular cluster, for example Caldwell 86 in ara (althara) constellation lie at a distance of 6000 ly from the galactic plane. So it cannot be detected by small telescopes. Even the brightest and biggest globular cluster can be seen only by telescope of aperture 15 cm.

Pulsating stars (Pulsars)

Stars which emit light signals and undergoing continuous expansion and contraction at regular intervals of time is called pulsating variable stars or shortly pulsars.

Stars which emit radiosignals are called radio pulsars, those which give out X-rays are called X-ray pulsars. It has also been discovered that some stars emit γ -ray pulsars.

First pulsar was detected in the year 1967 by Joselyn Bell and Anthony Hewish. This is named as PSR 1919 + 21. The time period of the pulse emitted by this pulsar is 1.337 seconds. For this discovery Anthony Hewish was awarded the physics Nobel Prize in the year 1974. In those days people believed that the signals are sent by some intelligent extraterrestrial creatures. But 1978 Thomas Gold and Franco Pachini suggested pulsars are rotating neutron stars.

The time period of the pulse is not the same for all pulsars. It varies from some milliseconds to 5 seconds. For example the time period of Crab pulsar is 0.033 second. It is due to the high precision of time period the pulsars are regarded as the cosmic clocks.

On the basis of the H-R diagram we can explain pulsars. We found that when star's masses are far massive than the Sun that contract and move horizontally across the H-R diagram, while at the same time they get hotter but remain at a constant luminosity. As they move across the H-R diagram these stars are unstable and change their size by alternately by contracting and expanding.

There are several classes of pulsars such as long period variables, the Cepheid variables, and RR Lyrae variables. These will be discussed later. The figure below shows where these different classes of pulsars reside on the H-R diagram.

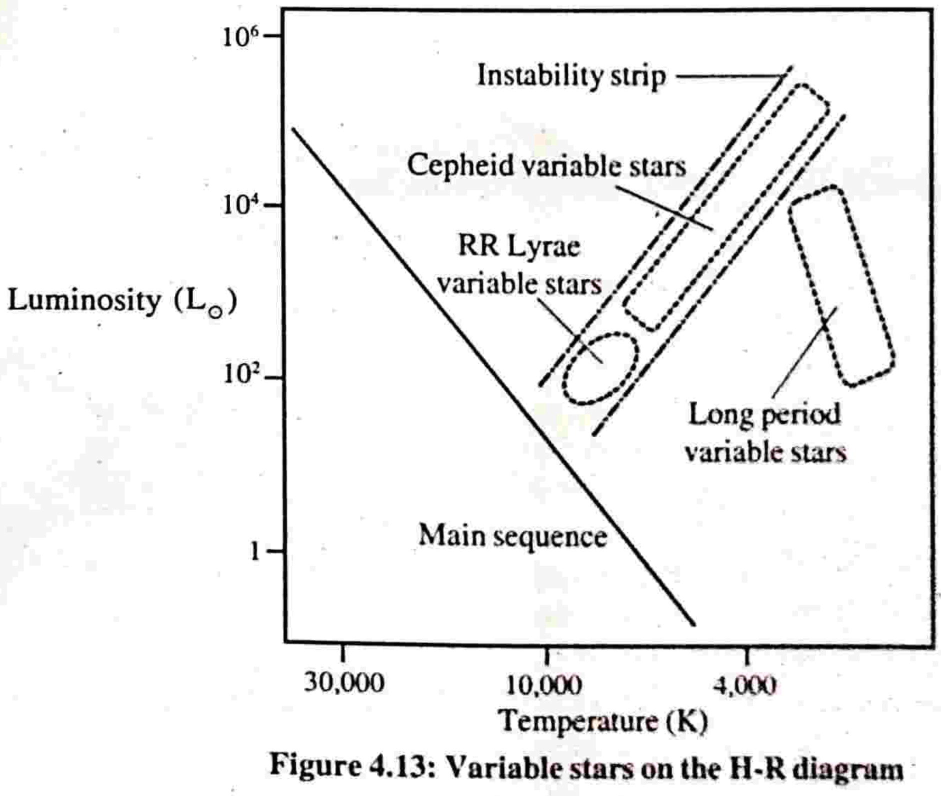


Figure 4.13: Variable stars on the H-R diagram

Why do stars pulsate

It has been realised that some stars pulsate not due to the variations in the rate of energy production in the inner core but due to changes in the rate at which energy can escape from the star. The explanation is as follows.

Imagine a normal star, where there is a perfect balance between the gravitational force acting inward and the force due to radiation pressure acting outward. Now suppose that somehow the force due to radiation pressure of the star at the out layers exceeds the gravitational force of the outer layers the star would begin to expand at the outer layers. As the star expands naturally gravity force falls down $\left(F \propto \frac{1}{r^2}\right)$, but the pressure force will fall at a faster rate. A time would then come when the star will have expanded to a large size such that hydrostatic equilibrium is once again regained. This does not mean that star would stop expanding. It is due to inertia expansion continues, thereby upsetting the balance. But the gravity pull will stop the expansion as the radiation force is too low to balance the gravity. So the outer layers would begin to fall inward. At this point gravity will rise again $\left(F \propto \frac{1}{r^2}\right)$ but less than the pressure. The outer layers will fall past the balance point until the force of pressure would prevent any further fall, so would come to a halt. The process continues forever. As a result star pulsates. See figure 4.14.

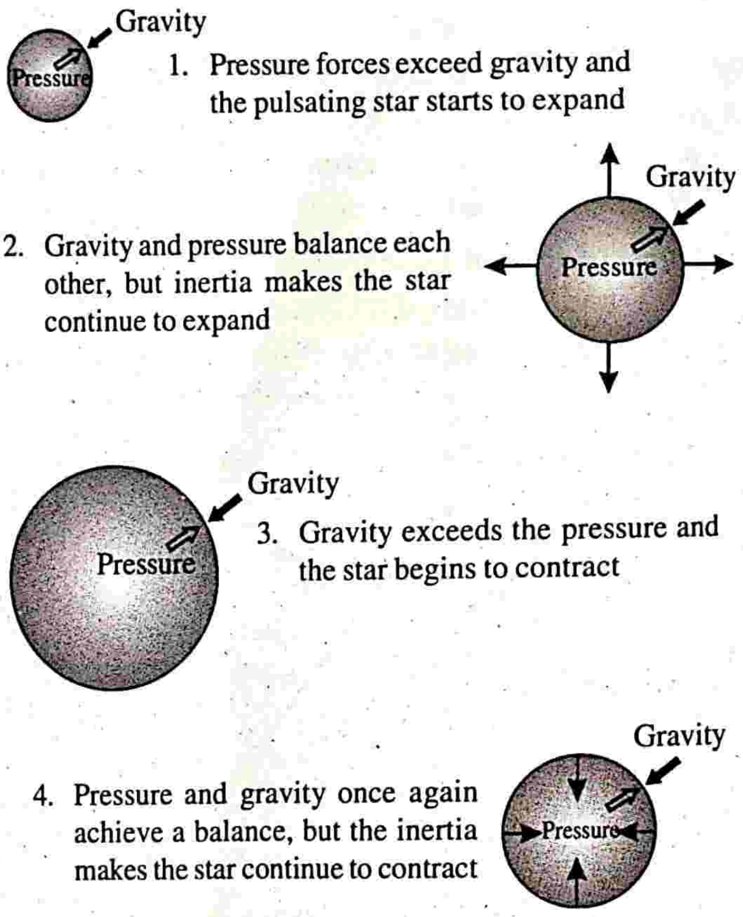


Figure 4.14: Gravity and pressure during the pulsation cycle of a pulsating star

The pulsating star behaves something like the oscillation of a spring attached to a mass. In this case there is a balancing and unbalancing between gravity and tension acting on the spring. After sometime the oscillation will die due to the presence of damping force. In order to sustain the oscillation it requires outward push. In the case of pulsars what is the extra force that would sustain the expansion and contracting was a challenging problem to astronomers.

In 1914 the British astronomer Aurther Eddington gave an explanation for this. He suggested that a star pulsated because its opacity increases more when the gas is compressed than when it is expanded. Heat is trapped in the outer layers if a star is compressed, which increases the internal pressure this in turn pushes the outer layers. As the star expands the heat will escape and so the internal pressure falls and the stars surface drops inward.

In 1960, the American astronomer Johncox further developed the idea of Eddington and proved that helium is the key to the pulsation of stars. When a star contracts, the gas beneath its surface gets hotter, but the extra heat does not raise the temperature instead, it ionises the helium. This ionised helium is very good at absorbing radiation. In other words, it becomes more opaque and absorbs radiant energy flowing outward through it. This trapped heat makes the star expand. This then provides the push that propels the surface layers outward. As the star expands, electrons and helium ions recombine and this causes the gas to become more transparent.

In effect we can say that for sustained pulsations star must have a layer beneath its surface in which helium is ionised. The existence of such a layer depends on the size and mass of the star as well as on the temperature. The range of this temperature is from 5000 to 8000 K. There is a region on the H-R diagram, where such an area exists and it is the location of the pulsars. This is called the instability strip. The Cepheid variable pulsars and RR Lyrae pulsars are found in this region.

Cepheid variables and the period-luminosity relationship

Cepheus is an important and noteable constellation in the northern celestial sphere. It lies between Cassiopeia and Draco (Vyali) constellations. According to Greek mythology the constellation is the replica of king Cepheus of Ethiopia, hence the name Cepheus constellation. This constellation contains so many pulsars such as delta cephei, mucephei, VV cep, lambda cephei etc. δ- cephei is a pulsar with periodicity 5.4 seconds. It is a yellow giant star whose luminosity changes by a factor of two over 5.4 seconds. It has a companion star with blue colour. This means that it is a binary star. Stars which contract and expand with a constant periodity are called are Cepheid variables. Among these groups of stars the first star to be discovered was δ- cephei variable star. **All stars discovered after δ- cephei were called as Cepheid variables.** Variation of δ- cephei in luminosity, size and temperature versus time period are plotted in the same graph.

From the graph it can be seen that its luminosity and temperature have a maximum value when its size has a minimum value and vice-versa. That is its size is at its maximum when its luminosity and temperature are at minimum.

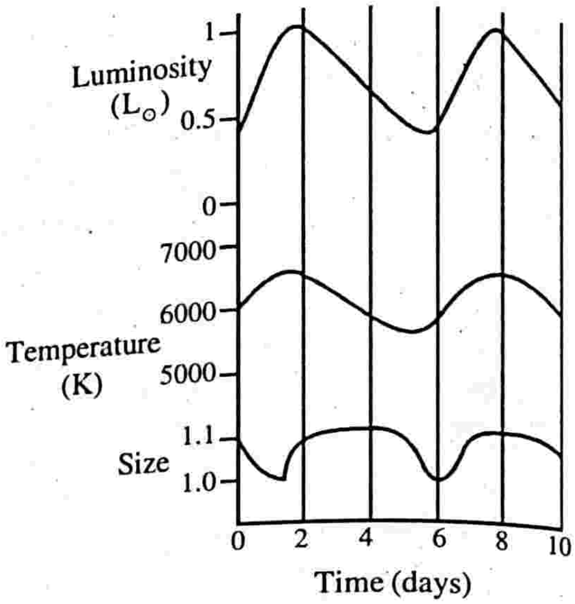


Figure 4.15: The size, temperature and luminosity of δ- cephei during one period

The study of Cepheids are very important for two reasons. (1) The Cepheids are very luminous ($100L_\odot$ to $10{,}000L_\odot$) they can be seen even though they are at great distances (few million parsecs) (2) There exists a relationship between the pulsation period and its average luminosity. This is called period-luminosity relationship.

If a star can be identified as Cephied its period can be measured. Then its luminosity and its and its absolute magnitude can be determined. This can then be used along with its apparent magnitude to determine its distance.

Cepheid stars are classified into two according to the amount of metals present in the stars outer layers which a determines how it pulsates. This is because metals can have substational effect on the opacity of the gas. If a cepheid is a metal rich population I star it is called a type I Cepheid and if it is a metal-poor population II star, it is called type II Cepheid. Period-luminosity relationship for the two types of cepheids are shown in figure (4.16).

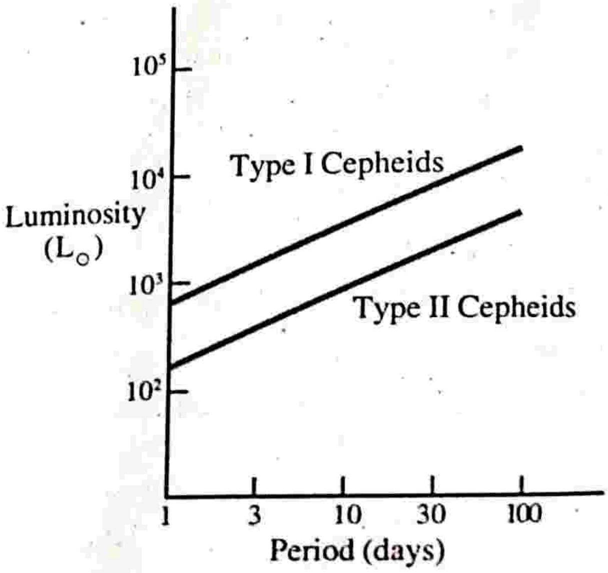


Figure 4.16: Period-luminosity relationshp for the two types of Cepheid variable star

Note

Population I star

These are bright, supergiant, main sequence stars with high luminosity. Examples O-type, B-type and members of galactic clusters and δ- cephei.

Population II star

These are old stars found in globular clusters. These are also called as ω-Virgins.

Examples: RR Lyrae and the central stars of planetary nebulae.

Temperature and mass of Cepheids

The period luminosity relationship comes about because the more massive stars are also the most luminous stars as they cross the H-R diagram during core helium burning. These massive stars are also larger in size and lower in density during this period of core-helium burning and the period with which a star pulsates is larger for lower densities. So the massive pulsating stars have greater luminosities and longer periods. This is shown in figure below.

We have seen that old high mass stars have evolutionary tracks that cross back and forth in the H-R diagram and thus will intercept the upper and of the instability strip. Such stars become cepheids when the helium ionises at just the right depth to drive the pulsations. Those stars on the left (high temperature) of the instability strip will have helium ionisation occurring too close to the surface and involve only a small fraction of stars mass. The stars on the right (low temperature) side will have convection in the stars outer layers and this will prevent the storage of the heat necessary to drive the pulsations. Thus Cepheid variable stars can only exist in a very narrow temperature range.

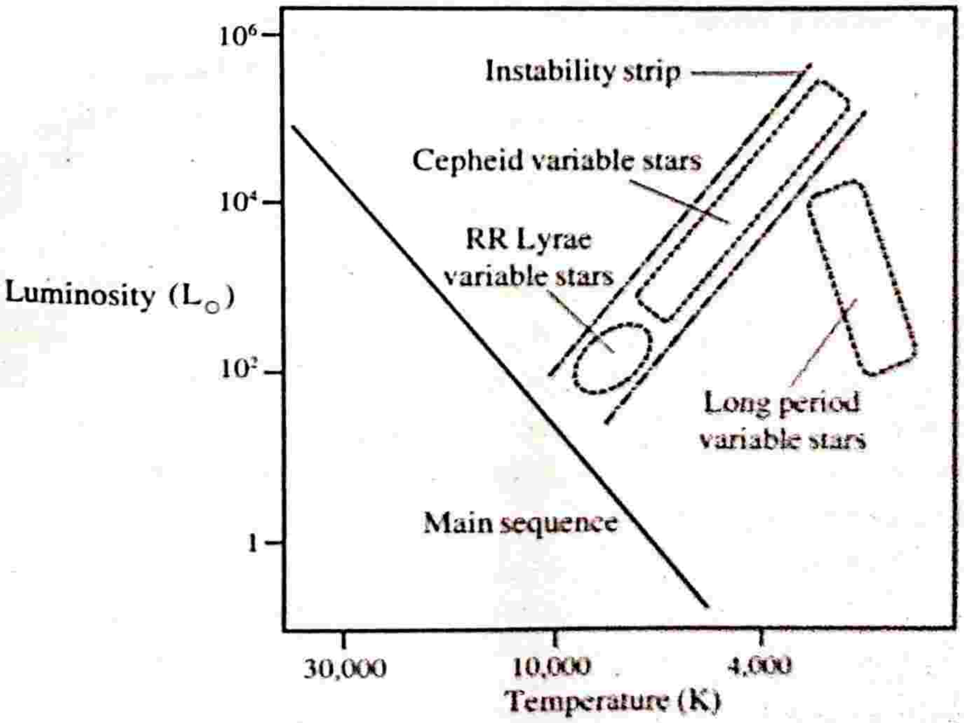


Figure 4.17: Instability strip and evolutionary tracks for stars of different mass

The death of stars

So far we learned about the formation of protostar, pre-main sequence stage, main sequence stage and red giant. It is the mass of a star decides how it will end its life. Low mass stars can end their lives in planetary nebulae before proceeding to white dwarf stars, where as high mass stars end their lives in supernova explosion. Depending upon the mass of the remants of supernova explosion it may become a neutron star or a blackhole. We shall see this one by one.

Now one very important question to be addressed stars live for millions, billions or even hundreds of billions of years, then how can we say affirmatively that a star dies? After all, we have only been in this planet for 4.5 billion years and studying astronomy for about 10,000 years. Fortunately, nevertheless it is possible to observe the many fundamentally different ways in which a star can end its life.

Asymptotic giant branch

We found that how a star becomes a red giant at the end of its main sequence life time. When a star becomes a red giant it moves left across the H-R diagram along the horizontal path as its luminosity remains almost constant. This is called the horizontal branch. When the star (Red giant) is in the horizontal branch it has helium burning core which is surrounded by a shell of hydrogen burning. It is due to α-triple process carbon and oxygen are the by-products present in the core. This will continue for a long period time about 100 million years. During this time all helium fuel has been used up and converted into carbon and oxygen when helium fuel exhaust nuclear fusion stops. Thus force of radiation is not able to balance the gravity force so the core contracts. However the core contraction is stopped by the degenerate electron pressure. The result of core contraction is the release of heat by the core into the helium gas surrounding the core. So helium burning begins in a thin shell around the carbon-oxygen core. This is called shell helium burning. Now the star enters a second red giant phase. **The hydrogen shell burning causes the outer layers to expand and cool. The energy from the helium burning star also causes the outer layers to expand and cool. So the low mass star rises into the red-giant region of the H-R diagram for a second time. This time red giant has greater luminosity. This phase of a star's life is called the asymptotic giant branch phase or AGB. The stars in this region are called AGB stars.**

The AGB star consists of a central core with carbon-oxygen mix surrounded by a helium burning shell which in turn is surrounded by a helium rich shell. This is further surrounded by a hydrogen burning shell.

Now the size of the star is gigantic. The core region is about the same size as the earth and total size is as large as the orbit of the earth. The luminosity of these stars are very high. For example an AGB star of mass $1M_{\odot}$ its luminosity is about $10,000L_{\odot}$. It is calculated that after 8 billion years our Sun becomes an AGB star.

There are so many AGB stars have been discovered. Some of them are star mira belongs to Ocetius (Thimingalam) constellation, R leonis belongs to Leo (Simham) constellation, R aquarri belongs to Aquaris (Kumbam) constellation.

The pictorial representation of the structure of an AGB star is given below.

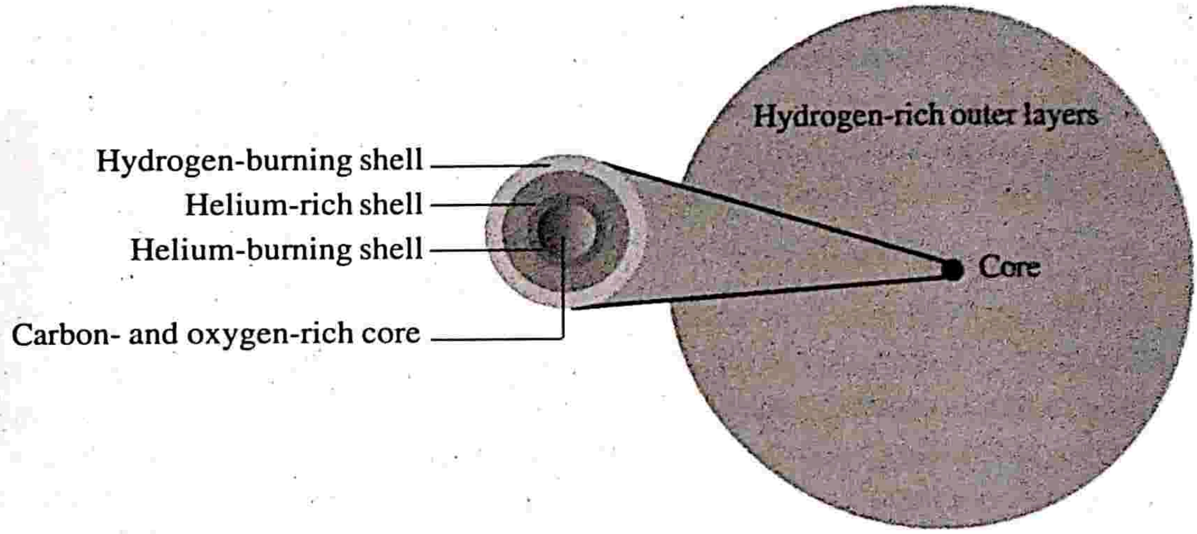


Figure 4.18: The structure of an AGB star

The end of AGB star's life

A red giant in phase I after about 100 million years reaches in phase II region called an AGB star. As time passes an AGB star grows in size and increase in its luminosity along with an increase in the rate of loss of mass. The mass loss can be $10^{-4}M_{\odot}$ per year. This means that our Sun after becoming an AGB star lives only for another 10,000 years. This shows AGB stars cannot go long away. If a star of mass less than $8M_{\odot}$ its stellar wind will strip away the outer layers almost down the core. This indicates the end of the AGB star. For stars greater $8M_{\odot}$, AGB star will end up in an explosion called supernova. This will be discussed later.

The formation of AGB star results in the production of carbon and oxygen via α-triple process. This will enrich the interstellar medium with carbon and oxygen. This indicates that the carbon in our body and all living creature on earth was formed many billions of years ago inside an AGB star by the α-triple process. It was then dredged up to the stars surface and expelled into space. Later by some means, it formed the precursor to the solar system and planets and all life on earth. This leads us to think that everything made of the stuff of stars.

Planetary nebulae

The interstellar space which consists of gases and dust particles of clouds is called as nebula. Nebula is a Latin word meaning cloud. In the study of stellar evolution nebulae plays an importance since nebulae are the birth places of stars. The debris of star explosion also come under the definition of nebula. Here we discuss about planetary nebulae.

A planetary nebula is an interstellar space containing gases and dust particles of clouds, fastly moving debris thrown away by the AGB stars at their ends of life with glowing core of stars. The planetary nebula was firstly discovered by astronomer Charles Messier in the year 1764. But the name was given by the astronomer William Herschel in the year 1783.

Formation of planetary nebulae

At the end of the AGB phase what remains is the degenerate core of carbon and oxygen surrounded by a thin shell in which hydrogen burning occurs. The dust ejected in AGB phase will be moving outward at tens of kilometres per second. As the debris moves away, the hot, dense and small core of the star will become visible. The aging star will undergo a series of bursts. During each burst ejects a shell of material into the interstellar space. The glowing inner core gives out almost constant luminosity for few thousand years and temperature of this comes about 30,000K to 100,000K. At this temperature star will emit huge amount of ultraviolet radiations, which can excite and ionise the expanding shell of gas. The totallity of all these is called as planetary nebula.

In our galaxy alone there are about 1500 planetary nebulae were discovered so far.

White dwarf stars

We found that how AGB stars end their lifes. AGB stars which have masses less than $4M_\odot$, the internal pressure and temperature produced inside the cores at its end of their life cannot ignite the carbon and oxygen in the cores. In this situation the stars throw away their outer layers leaving behind very hot carbon-oxygen rich cores. So the cores stopped their energy production by nuclear fusion and begins to cool down over a vast times scale. The cooling dead bodies or remnants of stars are called white dwarfs. As these stars emit white light and smaller in size they are called white dwarfs. The size of such stars are about 300 kilometres only.

Electron degeneracy

As the star sheds away its outer layer, it begins to contract. As the size decreases the mass of the white dwarf increases so the gravity pulls increases. The increase in mass and decrease in size is unlikely to our thinking. But this is true for white dwarfs. This is because of high density increase. The temperature that exists in the core brings the electrons to a peculiar state of affair called degeneracy. The degeneracy is a quantum phenomenon. According to Paulis exclusion principle no two electrons can occupy the same quantum state, so electrons progressively go to higher energy states to occupy. As a result they acquire high velocity and pressure. This pressure is called degenerate pressure. The force of degenerate pressure balances the gravity pull of the contracting star. This is what is happening inside a white dwarf. It is further emphasised that larger the white dwarf's mass smaller its size.

The Chandrasekhar limit

It is due to the degeneracy of matter inside the core, the density of the star increases so also its mass. The increase in mass results in increase gravitational pull, so the size of the star decreases. This means that when more and more degenerate matter is formed the size of the star becomes smaller and smaller. However this increase in mass cannot go indefinitely. **It has been calculated by the Indian astrophysicist Subramanyam Chandrasekhar that there is a maximum limit to the mass attained by white dwarfs. The mass is about $1.4M_{\odot}$. This limiting mass of white dwarfs is called Chandrasekhar limit.** For this discovery Subramanyam Chandrasekhar was awarded the physics Nobel Prize in the year 1983. When the mass of a star exceeds this mass limit $1.4M_{\odot}$, the force due to degenerate radiation pressure cannot balance the gravity pull. As a result star again contracts thereby electrons and protons inside the core fuses to form neutrons. Depending upon the mass of the star it may become a neutron star or a blackhole.

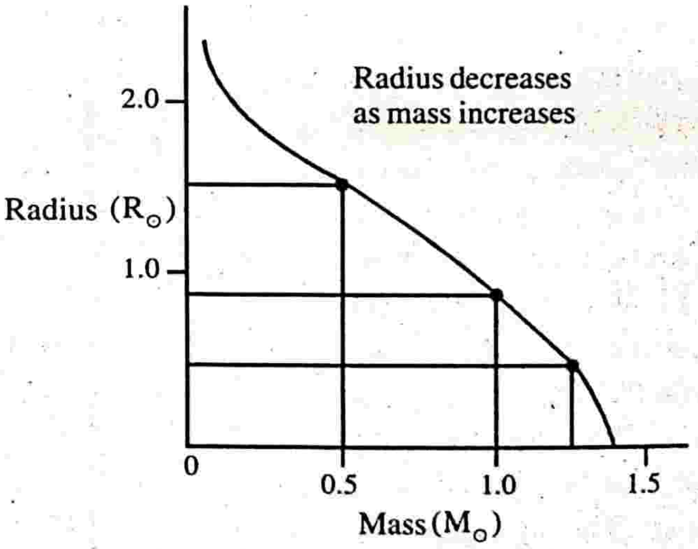


Figure 4.19: Mass-radius relationship for white dwarf stars

The mass-radius relationship of white dwarf stars are depicted in the figure 4.19.

Note: The mass of the star is expressed in terms of $M_{\odot}$ and radius is expressed in terms of that of earth ($M_{\odot}$).

Which stars become white dwarfs in their old age. The stars whose mass is less than $1.4M_{\odot}$ in their old age become white dwarfs. The star of types O, B and A which have larger masses can also become white dwarfs provided, they shed of their masses during their AGB phase II. After shed of mass if the mass is less than $1.4M_{\odot}$ become white dwarf. On the other hand they become neutron stars or black holes.

The final question to be answered is "what is white dwarf star made of"? It consists of mainly ionised oxygen and carbon atoms along with fast moving degenerate electrons. As the star cools down the electric forces between ions dominate over their random thermal motion. So ions no longer move freely but are aligned in orderly fashion and they behave like a giant crystal lattice. In this crystal lattice the degenerate electrons move freely in this giant crystal like electrons move freely in a copper wire. The density of white dwarf is about 10^9 kgm^{-3}. This is about one million times the density of water (10^3 kgm^{-3}). For example a teaspoon of white dwarf weights about 5.5 tonnes equal to the weight of an element.

$$M = V\rho, \quad V = 5.5\text{cm}^3 = 5.5\times10^{-6}\text{m}^3$$

$$\therefore \quad M = 5.5\times10^{-6}\times10^{9} = 5.5\times10^{3}\text{kg}$$

$$M = 5.5 \text{ tonnes.}$$

Volume of the teaspoon is 5.5 cm^3 on the average.

White dwarf evolution

When an AGB phase II star becomes a white dwarf it shrinks to an ultimate size with no nuclear fuel. However it will still have a very hot core with immense heat so the surface temperature is very high. For example the surface temperature of white dwarf Sirius B (the companion of Sirius A) is about 30,000K. As time passes heat will be radiated into space and they become cool, so their luminosity become lesser. The more massive white dwarfs will have smaller surface are so also their luminosity, for a given temperature. When we represent this

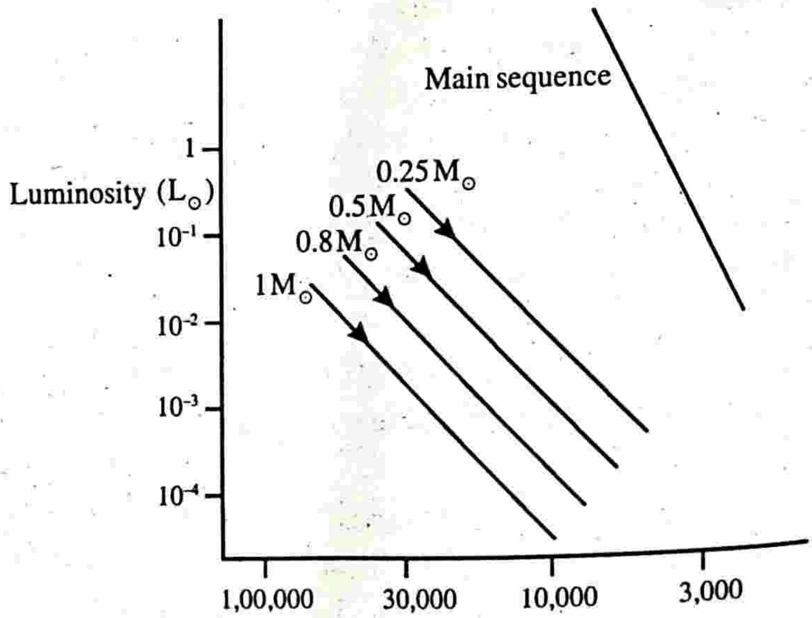


Figure 4.20: White dwarf evolutionary tracks

on a H-R diagram the evolution tracks of massive stars are below those of the less-massive stars. An H-R diagram showing the evolutionary tracks of white dwarf stars with different masses are shown Figure 4.20.

The theoretical model of the evolution of white dwarfs gives us important informations. The white dwarfs with a mass of $0.6M_\odot$ will fade to $0.1L_\odot$ in about 20 million years. Any further reduction in luminosity takes longer times. This means that it will take 300 million years to fade to about $0.01L_\odot$ and billion years to take to get to $0.001L_\odot$. It will take about 6 billion years to reach about $0.0001L_\odot$. At this luminosity white dwarf will have the same temperature and colour (white) of the Sun. The white dwarfs with masses greater than $0.6M_\odot$ have more heat content and so will take even longer time to cool down and grow faint.

In the case of the sun, it will eject most of mass into space and eventually ends up about the same size as the earth, but luminosity changes dramatically and it becomes $0.01L_\odot$. After 5 billion years the luminosity becomes $10^{-5}L_\odot$ and gradually fades away from our view.

The white dwarf origins

All, so far, discovered white dwarfs are found to be originated from the central part of the planetary nebulae where AGB II phase stars were living and end their lifes. The masses of stars were also found in well agreement with Chandrasekhar limit ($1.4M_\odot$). But even though theory matches with experimental observations, there is still uncertainty in the initial mass of the stars leading to white dwarfs. Current ideas suggest a limit of $8M_\odot$. Those main sequence stars that have between 2 and $8M_\odot$ produce white dwarfs of mass of 0.7 and $1.4M_\odot$, where as main sequence star less than $2M_\odot$ produce white dwarfs of mass 0.6 to $0.7M_\odot$. The lower mass stars in the main sequence have incredibly long lifetimes, the universe is not old enough to produce white dwarfs. From this we can conclude that there are no white dwarfs with mass less than $0.6M_\odot$. The time taken for the evolution from giant stars to white dwarf can be in between 10,000 to 100,000 years.

Some examples of white dwarf stars are Sirius B belongs to Canis major (big dog), Procyon B belongs to Canis minor (small dog), 0 eradani 40 belongs to Eradinus (river) and Van Maneen's star Wolf 83 belong to Pisces (fish) constellations.

High mass stars and nuclear burning

The life of high-mass stars are different from these of low-mass stars. Throughout the entire mass of a low-mass star only two nuclear reaction occur. The hydrogen burning and helium burning. The by-products of this burning are carbon and oxygen.

In the case of zero age mass greater than $4M_{\odot}$, the temperature involved is very high so several other nuclear reactions will also occur. Since the carbon-oxygen core is more massive than the Chandrasekhar limit $1.4M_{\odot}$ the gravity pull is very high and so the degenerate pressure cannot stop the core from contraction and heating.

After hydrogen burning and helium burning some helium will be left in the core. This cannot initiate further nuclear reaction. But the process of helium capture occurs. This is the process of fusing of helium into progressively heavier elements. The core begins to contract with rise in temperature to about 600 million kelvin. At this high temperature, the helium capture can give rise to carbon burning and the carbon can be fused into heavier elements such as oxygen, neon, sodium and magnesium. The carbon fusion produces a new source of energy which restores the balance between pressure and gravity temporarily.

If the star has mass greater than $8M_{\odot}$ further reactions will occur. In this phase, the carbon burning may only last a few hundred years. The core contracts further and temperature rises. When the temperature reaches 1 billion kelvin, the neon burning begins. Neon is the by-product of earlier carbon burning reaction. In neon burning there is an increase in the amount of oxygen and magnesium in the core. The neon reaction lasts as little as one year. In each stage of reaction temperature increases there by further reactions occur. When the temperature reaches 1.5 million kelvin oxygen burning will occur with the production of sulphur. When the temperature reaches to 2.7 million kelvin silicon burning occurs. This reaction produces several nuclei from sulphur to iron.

Despite the very dramatic events that are occurring inside the high-mass star its outward appearance changes only slowly. When each stage of core nuclear reaction stops, the surrounding shell burning intensifies and therefore inflates the star's outer layers. Then each time the core flares up again and begins further reactions, the outer layers may contract slightly. This is the reason why the evolutionary track of high mass stars moves in zig-zag path. See figure 4.11.

Some of the reactions that occur also release neutrons. They collide with positive charged ions and combine with them. The absorption of neutrons by nuclei is termed neutron capture. In this reaction many elements and isotopes are produced.

It is due to stars high mass events occur at a very fast rate, with each successive stage of nuclear burning proceeding at an ever increasing rate. Calculations show that for 20-25$M_\odot$ zero age stars the carbon burning stage can last for about 600 years, while neon burning stage can be as short as one year. The oxygen burning last only 6 months and the silicon burning only one day.

At each core burning, a new shell of material is formed around the core of the high mass star and after several such stages the internal structure of the star resembles an onion. See figure below.

Nuclear reactions are taking place in several different shells simultaneously and the energy released will heat a rapid rate such that the out layers can expand to huge size. The star now is called as supergiant. The luminosity and temperature will be very much higher than those of giant stars.

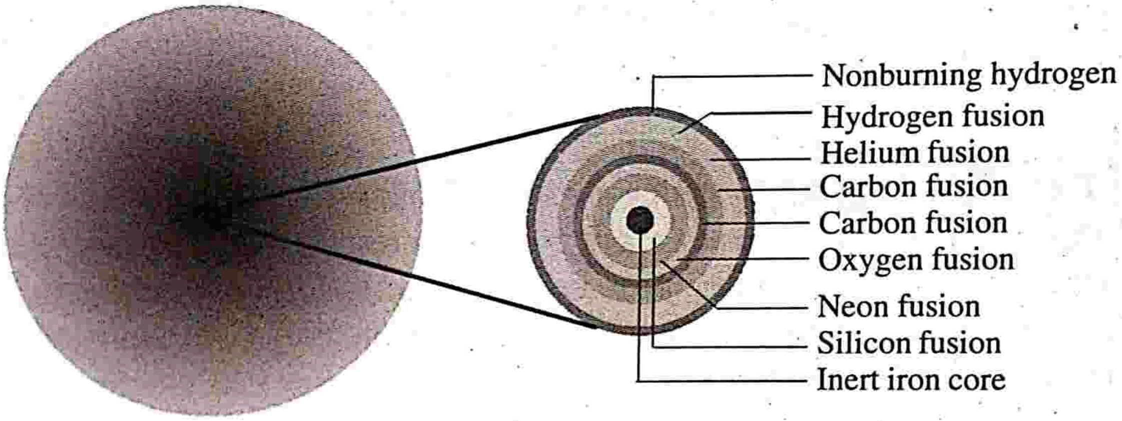


Figure 4.21: The multiple-layer structure of an old high-mass star 20 - 25$M_\odot$

Many of the brightest stars in the night sky are supergiants. Some examples are

1. Rigel and Betelgeuse in Orion (hunter) constellation.
2. Arcturus in Scorpius (scorpion) constellation
3. V.V. Cephi in Cepheus constellation

The size, temperature of the above supergiant stars are given below.

Name	Temperature in K	Size $M_\odot$
Rigel	11,000	——
Betelgeuse	3700	700
Arcturus	——	——
V.V Cephi	——	1990

Supernovae and formation of the elements

When a massive star becomes a supergiant, it cannot go on forever as such as there is only finite material to burn. Thus the star undergoes yet another change (gravitational collapse). It is star death. The change is highly catastrophic at the same time spectacular. This gravitational collapse of the star is called supernova.

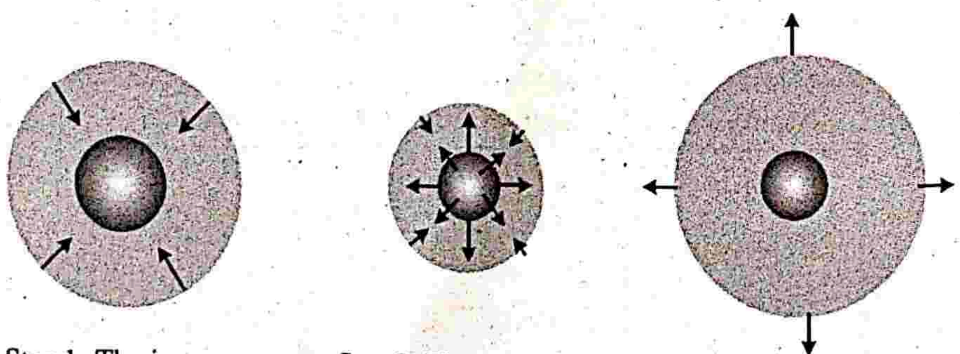
During the final days of supergiant, the core of inert iron, in which there are no nuclear reactions taking place, is surrounded by shells of silicon, oxygen, neon, carbon, helium and hydrogen. Since the mass is very heavy the force due to degenerate pressure cannot balance the gravity force. Hence the star undergoes collapse.

A consequence of core contraction is an increase in density, which in turn gives rise to a process called neutronisation. This is a process in which electrons react with protons in iron nuclei to form neutrons and neutrinos.

i.e. $$e^- + p \longrightarrow n + \upsilon$$

This results in speeding up of contraction (collapse). In seconds the core of radius of thousands of kilometres to about 50 kilometres. Then in few seconds it further contracts to 5 km. This time core temperature increases to about 500 million kelvin. The gravitational energy released as a result of the core collapse is equal to Sun's luminosity for several billion years. Most of this energy is in the form of neutrinos, but some is in the form of gamma rays, which are created due to the extremely hot core temperature. These gamma ray photons interact with iron nuclei resulting in the production of alpha particles. This process is called photodisintegration.

After a very short time of about 0.25 seconds, the core of mass of about $0.6M_\odot$ to $0.8M_\odot$ will reach a density equal to that of nuclei about $4\times10^{27}\,kgm^{-3}$. At this point neutrons become degenerate and force due to degenerate pressure balances gravitational pull and further contraction stops immediately and the inner most part



Step 1: The iron core collapses

Step 2: The neutron-rich core rebounds

Step 3: The shock wave moves outward

Figure 4.22: Evalutioin of a supernova explosion

of the core becomes rigid. This called a neutron star. The inner most part actually rebounds outward and pushes back against the rest of the infalling core, driving it outward in a pressure wave. This is called the core bounce. This is illustrated in figure 4.22.

At this stage the core cools down so also the pressure. The result is that the balancing will be upset. Owing to this the material surrounding the core falls inward at a speed close to 15% of the speed of light. This inward moving material encounters the outward moving pressure wave which moves at a speed of one sixth the speed of light. In just a fraction of a second the falling material now moves back outward towards the stars surface.

The upward moving wave of pressure speeds up as it encounters the less dense regions of the star and achieves a speed greater than the speed of sound wave. The pressure wave now becomes a shock wave. The neutrinos present in the core escape from the star in a few seconds but the shockwave takes few hours to reach the surface. Most of the material of the star is pushed outward by the shockwave and is expelled from the star at many thousands of kilometres per second. The energy released during this event is about 10^{49} J, which is 100 times more than the entire output of the Sun during the last 4.6 billion years. The visible light that we see during the event is only 1% of the energy released.

It has been proposed by astrophysicists that up to 96% material making up the star may be ejected into stellar medium that will be used in future generations of star formation. But before the matter is ejected, it is compressed to such a degree that new nuclear reactions can occur within it. It is these reactions that form all the elements that are heavier than iron. Elements such as tin, zinc, gold, mercury, lead, uranium etc. are produced. These elements that make up the solar system, the earth was formed long ago in a supernova.

From statistical considerations it is calculated that there should be about 100 supernovas in a year in our galaxy alone. In the year 1987 we observed a supernova in the large megallance cloud galaxy another one observed in our galaxy several hundred years ago. Since galaxy is filled with dust and gas they block the light coming from supernova, so it is very difficult to observe them. Now we believe that the stars Betelgeuse and Eta carina are on the verge of becoming supernovae.

Supernova remanants

Supernova remanant (SNR) is the totality that includes the debris of the explosion, the layers of the star that have been thrown into space and the remains of the core which is a neutron star.

The visibility of SNR depends on several factors such as its age, energy source that remains to make it shine and the type of supernova explosion.

As the remnant ages, its velocity will decrease from 10,000 kms^{-1} to about 200 kms^{-1}. During this time it will fade. A few SNRs have a neutron star at their centre that provides a replenishing source of energy to the far-flung material.

An example of SNR that undergoes this process is the crab nebula MI in Taurus (buffalo) constellation. What we see is the radiation produced by electrons travelling at velocities near the speed of light as they circle around the magnetic field. This radiation is called synchrotron radiation. This radiation is pearly, faint glow that we observe. Some SNRs glow as the speeding material interacts with dust grains and atoms in interstellar space, while others emit radiation due to the tremendous kinetic energies of the exploding material.

Caldwell 33 and 34 belongs Cygnus (swan) constellation, Messier I belongs to Taurus, sharpless 2-276 belongs to Orion (hunter) constellation are examples of supernova remanants.

Supernova types

Supernovae can be classified into two types depending on the spectra emitted by them. They are (i) type I supernovae and (ii) type II supernovae.

Type I supernovae

Supernovae which contain no emission lines of hydrogen in their spectra are called type I supernovae.

Type I can be further divided into types type Ia, type Ib and type Ic. Type Ia has absorption lines of ionised silicon and types Ib and Ic do not. Type Ib has helium absorption line whereas type Ic does not.

Type II supernovae

Supernovae which contain emission lines of hydrogen in their spectra are called type II supernovae.

Distinctions between various supernovae

(i) Types Ib, Ic and II are massive stars but type Ia stars have had their outer layers stripped away either by a strong stellar wind or action of a nearby star.

(ii) Type Ib, Ic and II are found near sites of star formation since massive stars have short lives. But type Ia supernovae are found in galaxies where star formation may be minimal or has even stopped altogether.

(iii) Type I supernovae involve nuclear energy and emit more energy in the form of electromagnetic radiation, whereas type II involve gravitational energy and emit enormous number of neutrinos.

Pulsars and neutron stars

We found that neutron stars are created at the middle of supernovae renanants. When a massive supergiant undergoes a type II supernova explosion, the outer layers thrown into space and what remains is the central core. The central core has become a neutron star. The neutrons in this star become degenerate due to the high density of the collapsing core. The neutron stars were predicted by Robert Oppenheimer and George Volkoff in the year 1939 on the basis of the calculated properties of a star made entirely of neutrons.

The actual structure of the star is not known completely, but there are many theoretical models that accurately describe the observations. Many of their properties are similar to those of white dwarfs. For instance, an increase in the mass of a neutron star will result in a decrease in radius with a range of radii from 10-15 km. The mass of the neutron star can be from $1.5\text{-}2.7M_{\odot}$.

The other two important properties of a neutron star is its rotation and magnetic field. A neutron star rotates hundreds or even thousands of times per second. It is due to conservation of angular momentum. When materials are thrown away from the star in arbitrary directions they pick up angular momentum. As it contracts its moment of inertia (I) decreases, so to conserve angular momentum angular velocity (ω) should increase as $I\omega$ is a constant. Another property is that, like every star has a magnetic field, neutron star also has magnetic field. The strength of the magnetic field is about 100 milliontesla.

Some neutron stars are believed to be in a binary system. These neutron stars are X-ray bursters leading to pulsars. We already discussed pulsars. The generally accepted model of a pulsar is in which the magnetic axis is tipped with respect to the axis of rotation. Very energetic particles travel along the magnetic field lines and beamed out from the magnetic poles. As the neutron star rotates around its rotation axis the beamed radiation sweeps across the earth and the pulse is detected.

Blackholes

When a star burns out of its fuel and its core mass is equal to three or more times of solar mass, it comes to the end of its life called blackhole. Blackhole is a superdense planetary material which neither emits nor reflects any light from it and appears to be black.

It is because of enormous gravitational pull and there is no opposing force inside (completely burnt out) to half this, blackhole continues to contract. A ray of light trying to leave the blackhole will be pulled back. That is even a ray of light cannot escape from it. The minimum mass of the blackhole is $3M_{\odot}$ but there is no upper limit for the mass of a blackhole. When the mass is greater than $10^6 M_\odot$, it is known as super massive blackhole.

A blackhole is described by three parameters (i) singularity, (ii) Schwarz's child radius and (iii) the event horizon.

Astrophysicists conjectured that there are three types of blackholes. They are (i) stellar blackholes (ii) primordial blackholes and (iii) super massive blackholes.

Stellar blackhole

Subramanyam Chandrasekhar established that when a star burns out of its hydrogen fuel, if the mass of the inner core is greater than $1.4M_\odot$, it undergoes gravitational collapse and becomes a neutron star with small radius. But if the mass of the inner core is greater than $3M_\odot$, the star continues its contraction due to gravitational collapse thereby overcoming the electron degeneracy and neutron degeneracy and ultimately attain a critical radius with small volume. As there is no signal can come out of this critical radius it is called event horizon.

Primordial blackholes

The study of Stephen Hawking indicates that during the time of big bang at some places matter experiences high pressure and undergoes gravitational collapse and creating micro blackholes. For instance an object of mass equal to that of earth when contracted to a radius of 1cm, then it becomes a micro blackhole. In these small blackholes quantum effect dominates. From these blackholes rays tunnel out or vapourise. This phenomenon is called hawking radiation. However there is no possibility of existence of these blackholes now. In strict sense micro blackholes are not blackholes.

Supermassive blackholes

Recent studies revealed that there are blackholes with masses 10^6-$10^9 M_\odot$ exist in our galaxy and in outer galaxies. These blackholes are called supermassive blackholes. It is shown by calculation that the age of the blackhole is proportional to the cube of its mass. Hawking shown that the age of stellar blackhole is about 10^{67} years where as that of the universe is only 10^{10} years.

There are so many theoretical models of blackholes. They are (i) Schwarzchild model (ii) Ker model (iii) Ker-Neumann model and (iv) Reissner-Nordstrom model. Schwarzchild blackholes are non-rotating and electrically neutral blackholes.

Rotating and electrically neutral blackholes are called Ker blackholes. Rotating and electrically charged blackholes are called Ker-Neumann blackholes.

In Reissner-Nordstrom model blackholes are non-rotating but electrical charged.

Among the four models Schwarzchild model is the simplest one. We discuss only about this blackhole. Before discussing blackholes in detail we have to recall what is escape velocity. Escape velocity (v_e) of an object is velocity that needs to escape the pull of gravity of a celestial object. It is given by

$$v_e = \sqrt{\frac{2GM}{R}}$$

where M is the mass of the celestial object and R is its radius.

Here our celestial object is the blackhole its escape velocity is greater than the velocity of light c. In the limiting condition we can take $v_e = c$.

$$\therefore \qquad c = \sqrt{\frac{2GM}{R}}$$

$$\text{or} \qquad R = \frac{2GM}{c^2}$$

Knowing G, the mass of the blackhole M and c we can calculate the radius of the blackhole. If we are dealing with a Schwarzchild blackhole, R is called Schwarzchild radius.

$$\text{i.e.} \qquad R_{sc} = \frac{2GM}{c^2}$$

substituting the values of G, M and c we get

$$R_{sc} = \frac{2 \times 6.67 \times 10^{-11} \times M_{\odot}}{(3 \times 10^8)^2}$$

$$R_{sc} = \frac{2 \times 6.67 \times 10^{-11} \times 2 \times 10^{30}}{9 \times 10^{16}} = 2964\,\text{m}$$

$$R_{sc} \approx 3\text{km}.$$

This critical radius of a blackhole whose mass is equal to one solar mass is called Schwarzchild radius.

Schwarzchild blackhole

Astronomer Karl Schwarzchild applied Albert Einstein's field equation in general relativity for blackholes. **He solved field equations under the assumption that the blackhole is non-rotating and electrically neutral, thereby he could be able to describe a blackhole relativistically. This is called Schwarzchild blackhole.**

When a star contracts, due to gravitational collapse, a radius less than Schwarzchild radius becomes a blackhole we can consider Schwarzchild radius as the event horizon. What happens to the matter that is compressed into event horizon depends upon the rotation of the blackhole. If the blackhole is non-rotating (Schwarzchild black hole is non-rotating) the matter collapses to point with spherical symmetry. Technically speaking the point to which the star collapses is called singularity. At this point the volume of the matter goes to zero and gravity becomes infinity. Owing to the enormous gravity, matter is compressed to a small region of space where the identity of matter is lost and the whole laws of physics will fall flat within this region of singularity. However a rotating Ker blackhole would not have to face the phenomenon of singularity. Then the event horizon of rotating blackholes are not spherical and their poles are flattened.

Though the blackhole cannot be seen, their existence can be predicted by their influence in the neighbourhood. For instance if a blackhole is a companion of a binary star they rotate about the centre of mass. By observing changes in the visible star we can calculate the mass and the distance of the other invisible companion. If the mass is greater than $3M_{\odot}$ we can conclude that companion is a blackhole. If one of the stars in the binary is a red giant and the other is a black hole, blackhole attracts matter from the outer layers of red giant by its enormous gravity. These attracted matter rotates about the black hole forming accretion disc. The matter in the accretion disc is in the plasma state when this matter fall into event horizon, owing to their enormous speed it emits X-rays. This X-ray sources in space indicate the presence of blackholes.

Recent experiments have shown that in the constellation Cygnus there is an X-ray source, Cygnus X–1 which consists of a supergiant revolving around a small invisible companion with a mass ten times that of the sun. The companion of Cygnus X–1 is thought of to be a blackhole. Recently X-ray observatories installed in space observed so many X-ray sources in space. Among these 75% are believed to blackholes.

UNIVERSITY MODEL QUESTIONS

Section A

(*Answer questions in about* **two** *or* **three** *sentences*)

Short answer type questions

1. What is stellar evolution?
2. What is a protostar?
3. What is an embryostar?

4. What is meant by gravitational equilibrium of a star?
5. What is an evolutionary track of a star?
6. What is Hayashi phase?
7. Draw the mass-luminosity graph.
8. What is the main difference between stars of mass greater than $4M_\odot$ and less than $0.4M_\odot$ show in their evolutionary track?
9. Write down the limitations of stars masses.
10. What is a brown dwarf?
11. What are galactic clusters? Give two examples?
12. What do you meant by population I stars? Write down their pecularities.
13. What is the use of observing galactic clusters?
14. Write down three origins of triggering star formation.
15. What constitutes the internal structure of the Sun?
16. What is photosphere?
17. What is convection zone of the Sun?
18. What is radiation zone?
19. What is proton-proton chain reaction?
20. What is meant by radom walk of photons in the Sun?
21. What is diffusion time?
22. What are the informations given by very long diffusion time?
23. Brightness of Sun is very insensitive to changes in the energy production. Justify.
24. What are binary stars? Give two examples.
25. Classify the binary stars.
26. What is a spectroscopic binary? Give an example.
27. What is an eclipsing binary? Give an example.
28. What is astrometric binary? Give an example.
29. What is a visual binary?
30. Define the terms (i) separation and (ii) position angle (PA).
31. What do you understand by the term ZAMS?
32. What is the difference between zams and main sequence star?
33. Define the lifetime of main sequence star.
34. Write down the relation between lifetime of main sequence star and it mass.
35. Show graphically, how does main sequence life time vary with mass.
36. Distinguish between O-type stars and K-type stars with reference to luminosity, temperature and life time.

37. What is a red giant? Give two examples.
38. Write down the nuclear fusion reaction of helium burning in the red giant?
39. What are the ashes of helium burning?
40. What is helium flash in red giants?
41. Draw an H-R diagram indicating main sequence and the evolutionary track of red giants?
42. The main sequence on the H-R diagram is a broad band not a line. Why?
43. What are globular clusters?
44. Write down any two properties of globular clusters.
45. What is colour-magnitude H-R diagram?
46. What are the uses of colour -magnitude H-R diagram?
47. Draw a colour magnitude H-R diagram.
48. Distinguish between galactic and globular clusters.
49. What are horizontal branch stars?
50. What is the significance of turn off point in the colour-magnitude H-R diagram?
51. What is the meaning of the missing part of main sequence in the colour -magnitude H-R diagram?
52. What is a pulsar?
53. What is the main cause of pulsation in pulsars?
54. What is instability strip?
55. Show pictorially the four stages of variation of gravity and pressure during the pulsating cycle of a pulsar.
56. What was the explanation given by Arthur Eddington for a pulsating star?
57. What are Cepheid variablès?
58. What is period-luminosity relationship?
59. What is the relation between size and period of a Cepheid?
60. What is type I Cepheid?
61. What is type II Cepheid?
62. Distinguish between type I and type II Cepheids.
63. How a star dies?
64. What are the possible forms of life of a star in its old age?
65. What is asymptotic giant branch?
66. What is an AGB star?
67. What is the structure of an AGB star?
68. Show the pictorial representation of the structure of an AGB star.
69. Distinguish between a red giant and an AGB star?

70. How does an AGB star ends its life?
71. We can imagine that everything on earth is made of the stuff of stars. Justify?
72. What is a nebula?
73. What is a planetary nebula?
74. What is a white dwarf?
75. What is Chandrasekhar limit?
76. What is electron degeneracy?
77. Draw graphically the mass-radius relationship of white dwards.
78. What is white dwarf stars made of?
79. Where does white dwarf originate from?
80. What is neutron capture?
81. What is a supergiant? Give two examples?
82. Show the structure of an old high-mass star.
83. What is supernova?
84. What is meant by neutronisation?
85. What is photo-disintegration process?
86. What is a neutron star?
87. What is SNR?
88. What are the factors on which the visibility of SNR depend?
89. Classify supernovae types.
90. Distinguish between type I and II supernovae.
91. Write down three properties of neutron star.
92. How does neutron star pulsate?
93. What is a blackhole?
94. Write down the names of three parameters that describe a blackhole.
95. What are the three types of blackhole?
96. What is Schwarzchild radius?
97. What is meant by singularity?
98. What is event horizon?

Section B

(*Answer questions in a* **paragraph** *of about half a page to one page*)

Paragraph / Problem type questions

1. Briefly explain how a protostar is formed.
2. How does a star reach a hydrogen burning main sequence star?
3. What are the informations that we obtain from an H-R diagram depicted with evolutionary tracks of stars?

4. What are the four main phases of a star before it reaches the main sequence?
5. Distinguish between the radiation process and convection process based on the masses of the stars in the evolutionary track.
6. Explain the process that occurs below and above the limiting masses of star formation.
7. Explain one of the mechanisms of triggering star formation.
8. Explain how does supernova explosion triggers further star formation.
9. Explain the proton-proton chain reaction in the Sun.
10. How does energy transport from the core of the Sun to its surface?
11. Show that the diffusion time of photons of the order of 10^5 years?
12. What are binary stars? Classify and explain them?
13. Explain the processes that taking place inside the core of main sequence star.
14. Explain the formation of red giants.
15. Explain the helium burning process in red giants.
16. Explain the process of helium flash.
17. What are the informations that can be obtained from colour -magnitude H-R diagram?
18. Why do stars pulsate? Explain.
19. Explain how an AGB star is formed.
20. Explain the end of an AGB star's life?
21. How planetary nebulae are formed?
22. How does a white dwarf evolve? Explain.
23. Explain how does a supergiant form.
24. How SNR can be observed?
25. What is a stellar blackhole?
26. What is a primordial blackhole?
27. What is a supermassive blackhole?
28. How does a Schwarzchild blackhole is formed?
29. How can we detect a blackhole?

Section C

(Answer questions in about two *pages)*

Long answer type question (Essay)

1. Explain the birth of star?